Lecture 13: Semiconductors lasers

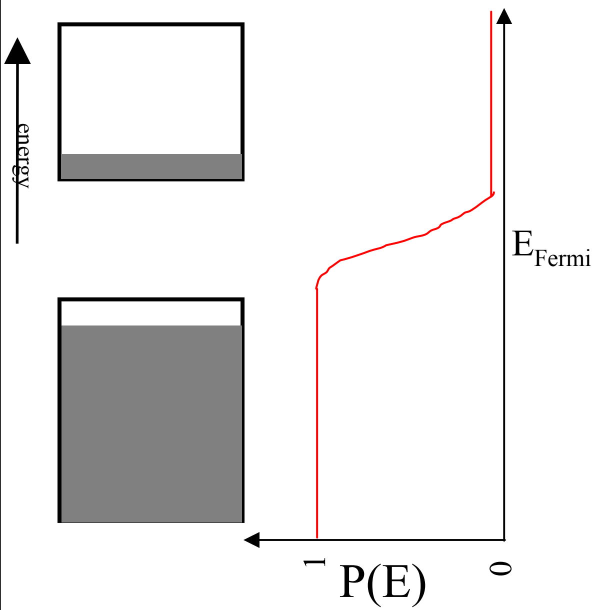
- Quasi-Fermi levels
- Optical properties
- pn junctions

Announcements

- Optical soliton talks next week
- Schedule for rest of quarter (extra credit talks)

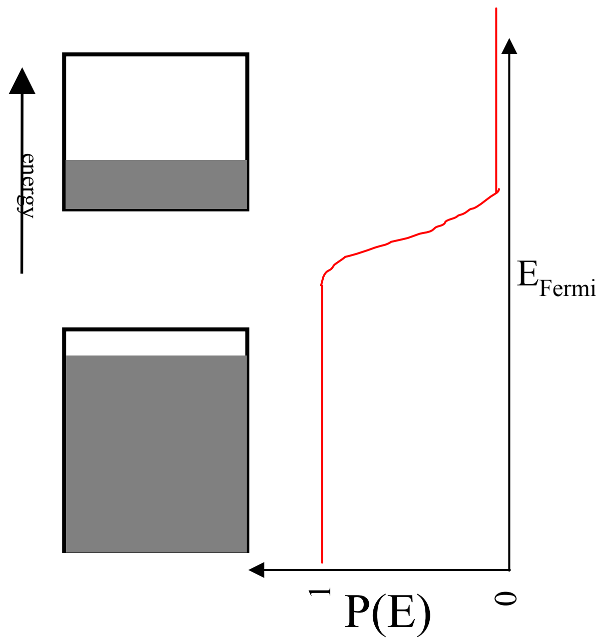
Last time:

Intrinsic:



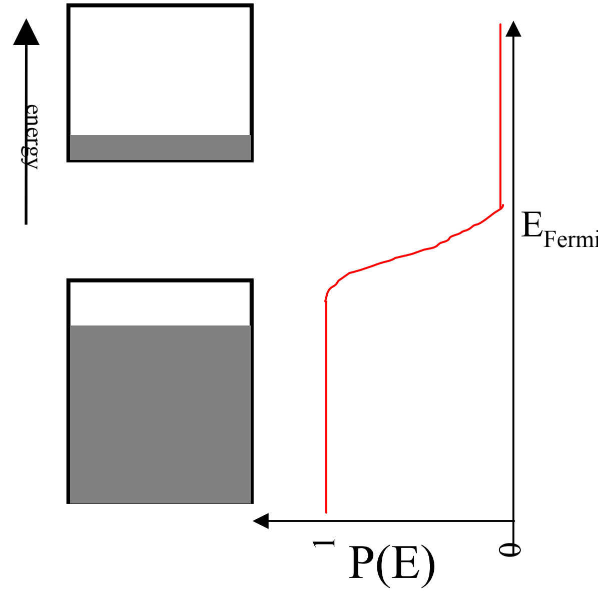
$n = p$

n-type:



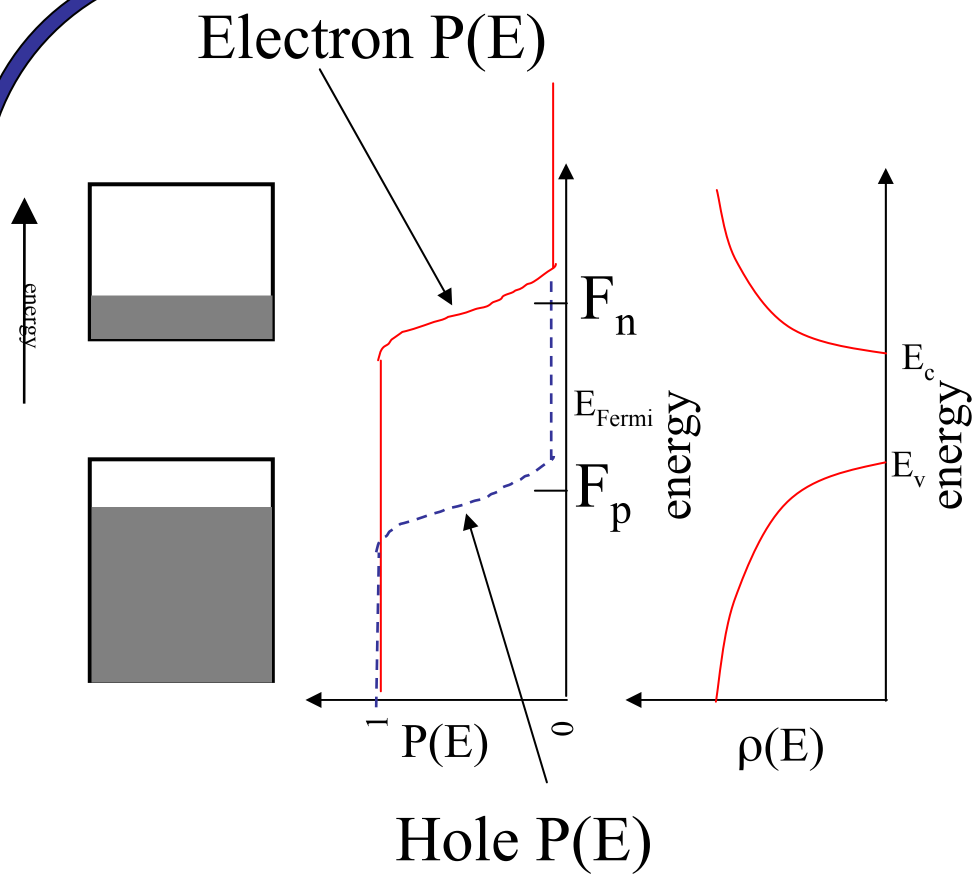
$n > p$

p-type:



$n < p$

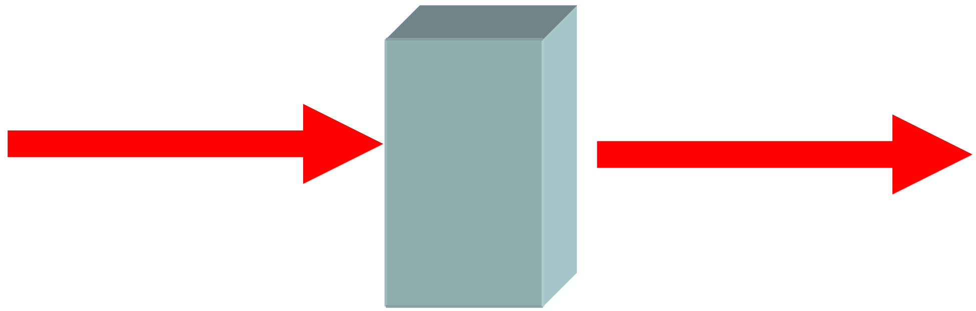
Quasi-Fermi levels:

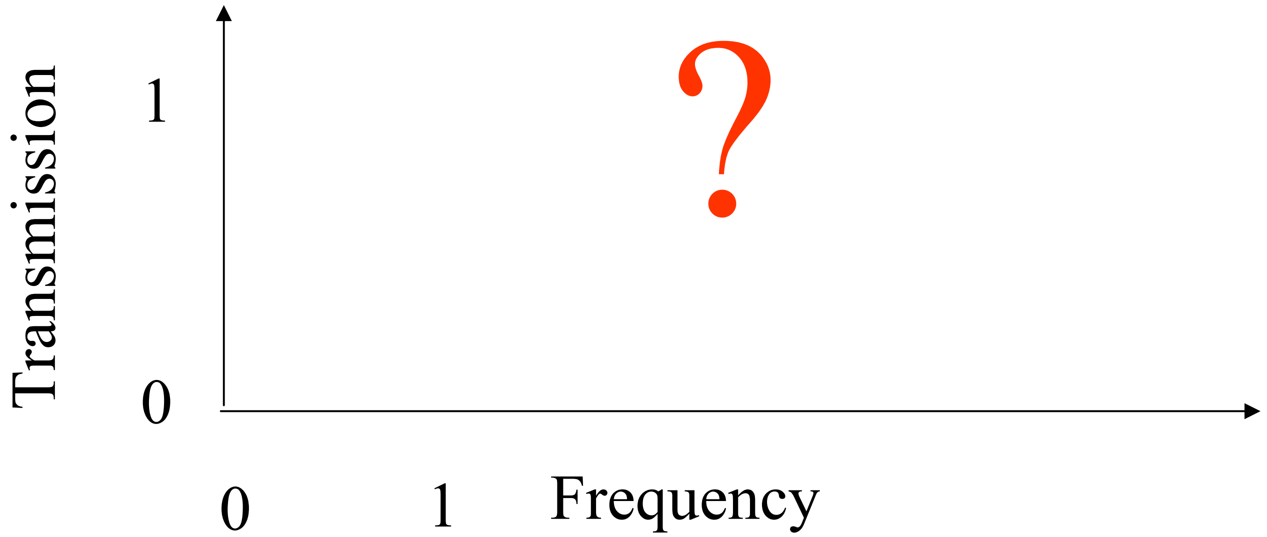


If we achieve this, electrons would spontaneously emit photons and tend to make $F_n = F_p$.

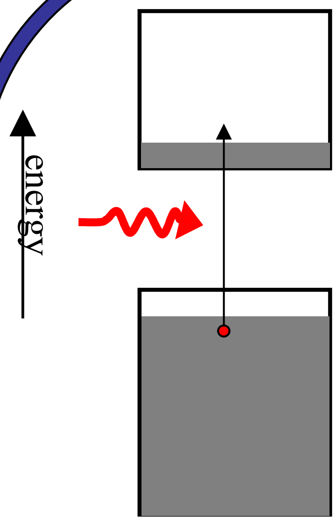
By injecting electrons from the n-side of a p-n diode, we can "pump" electrons into the system, thus maintaining the population inversion.

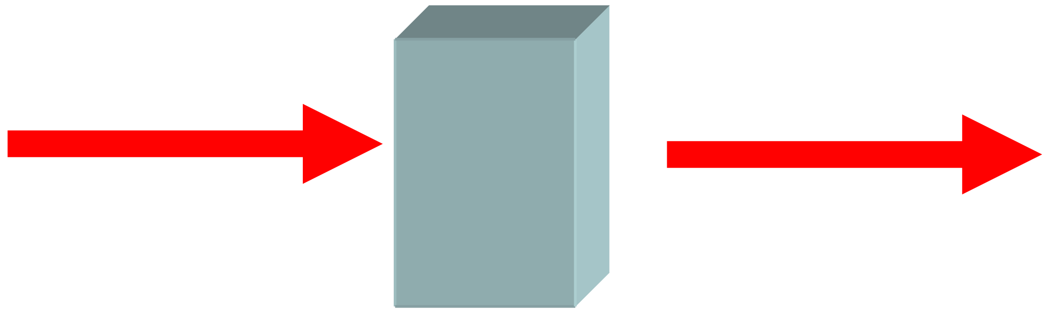
Optical absorption:

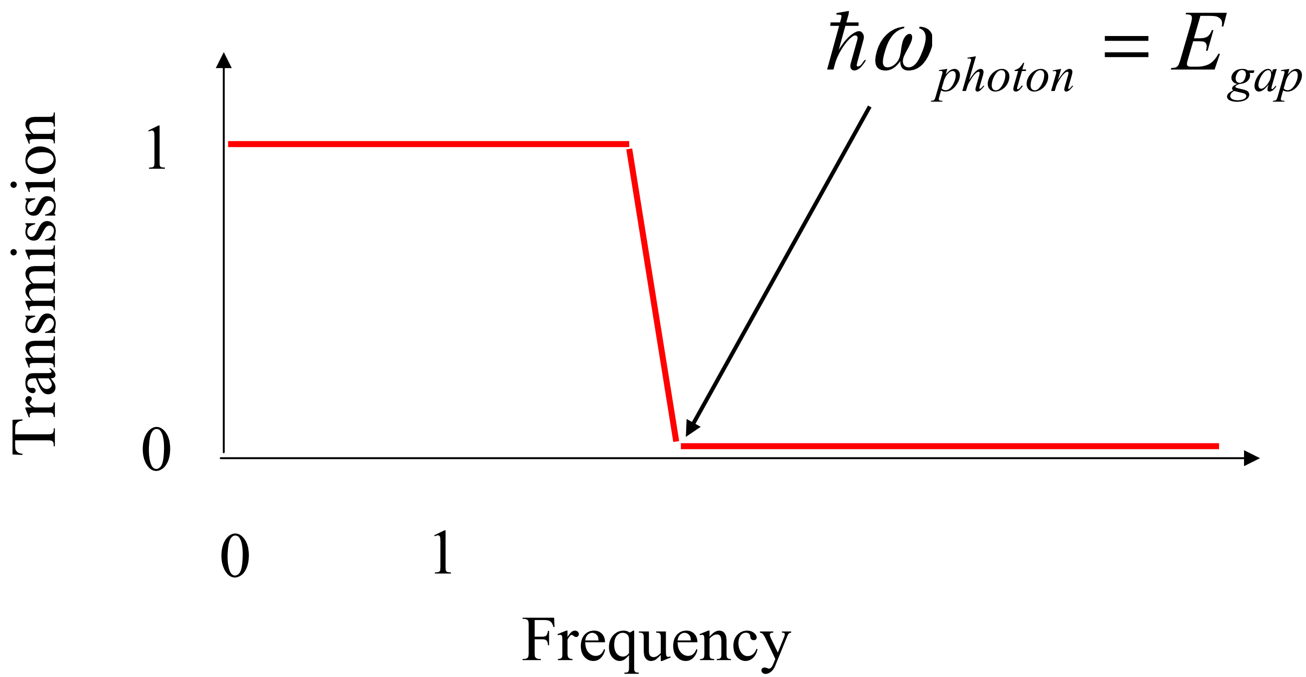




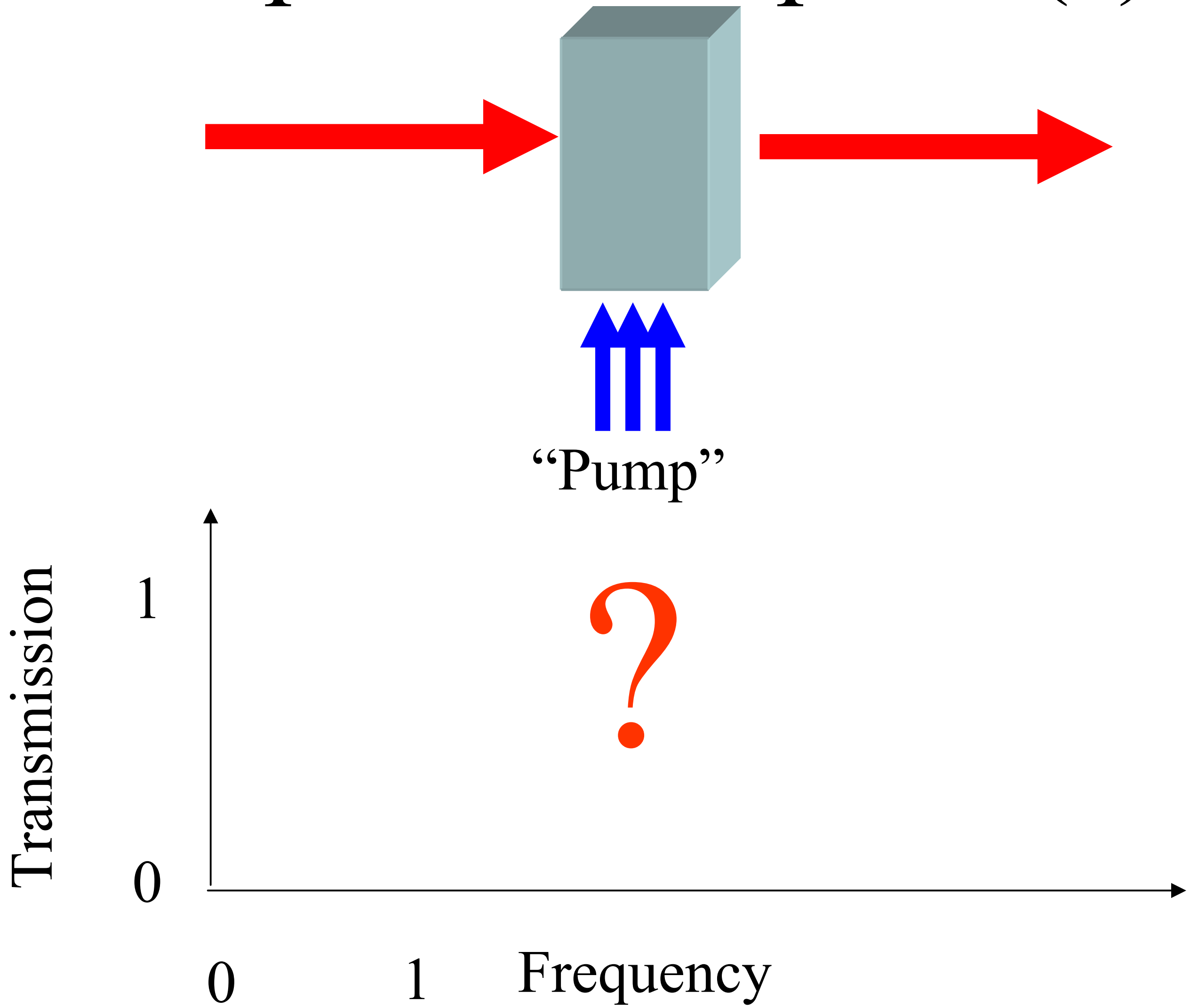
Optical absorption:



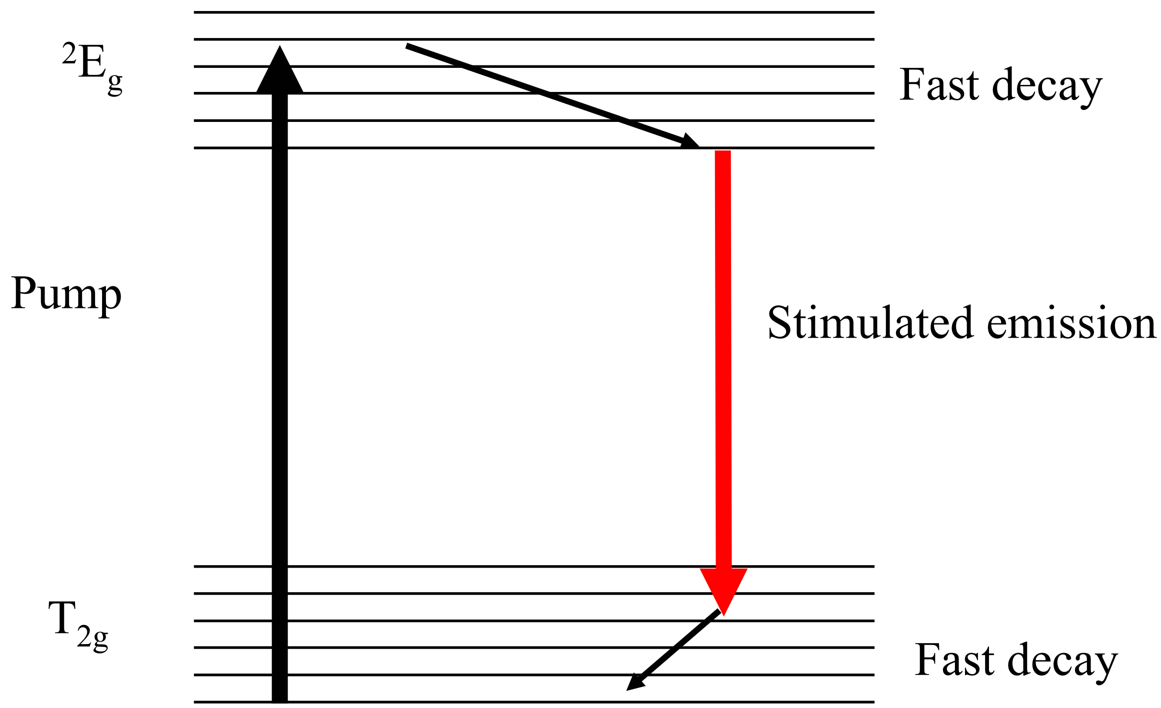




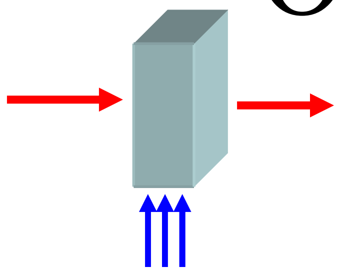
Optical absorption (?):

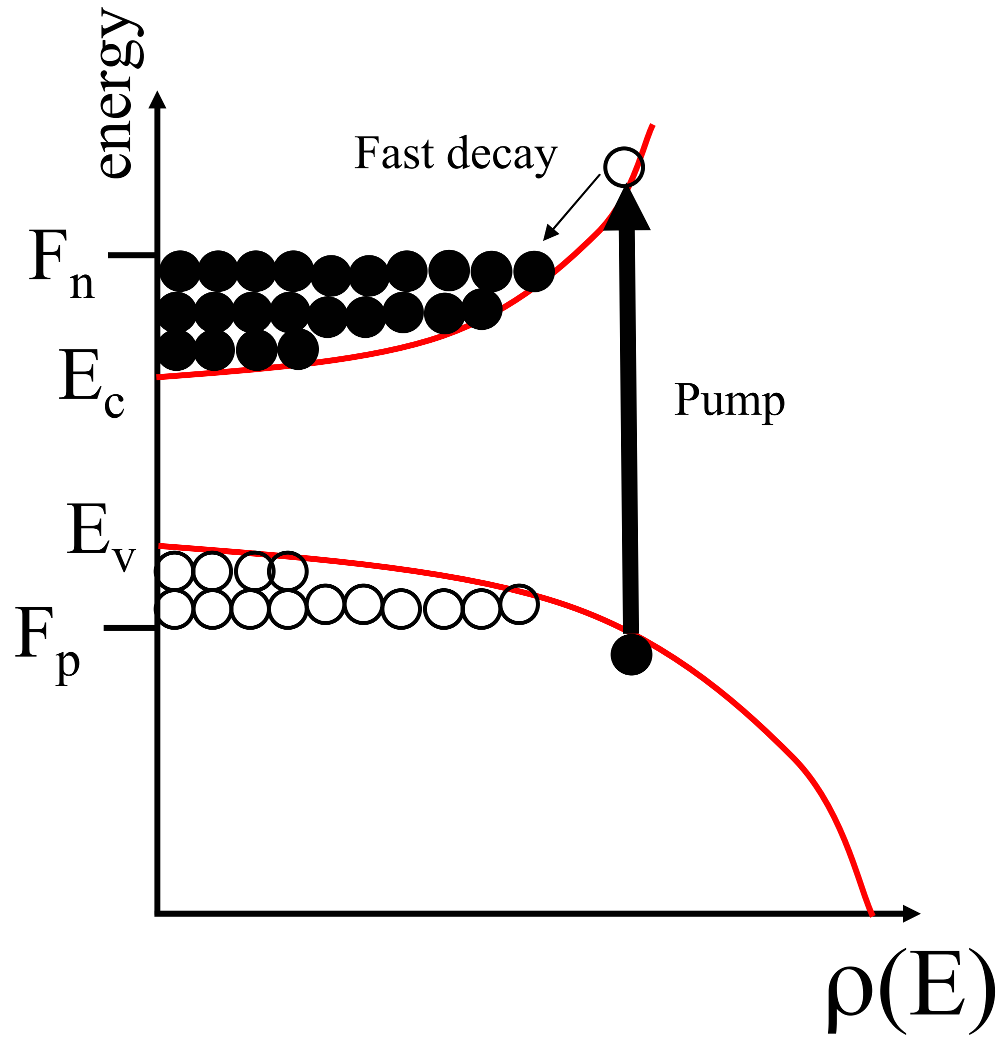


Recall Ti:Sapphire



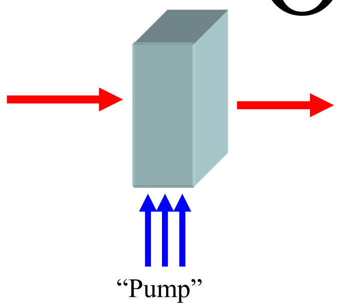
Optical absorption (?):

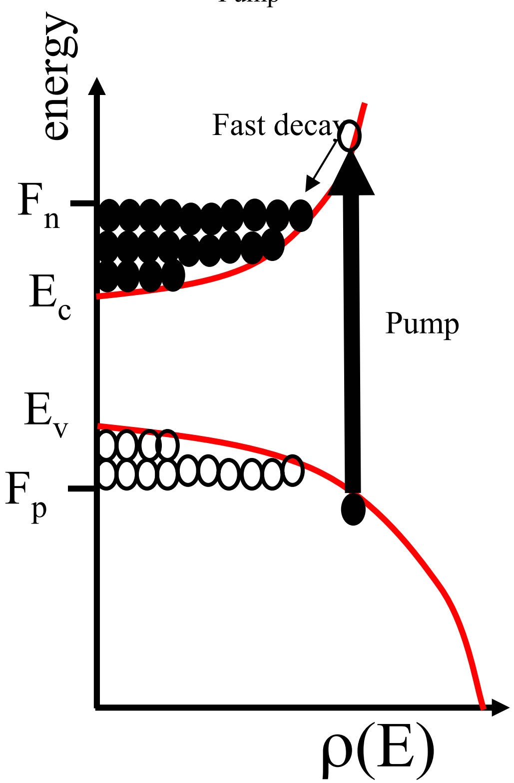


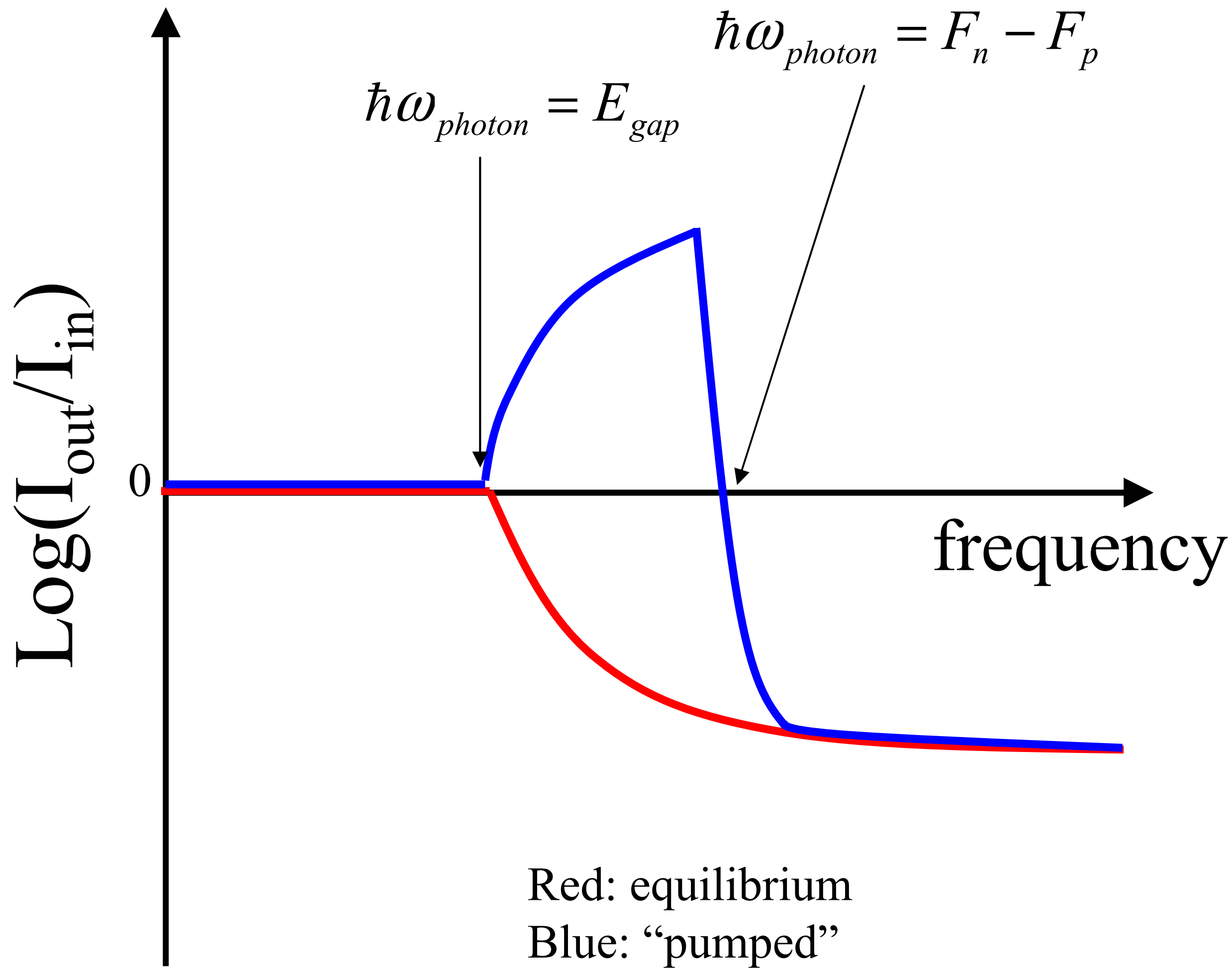


Discuss diagram in detail, including overlay of density of states, photon energy, and

Optical absorption (?):



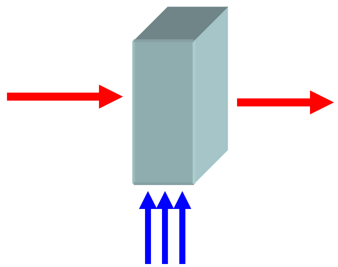




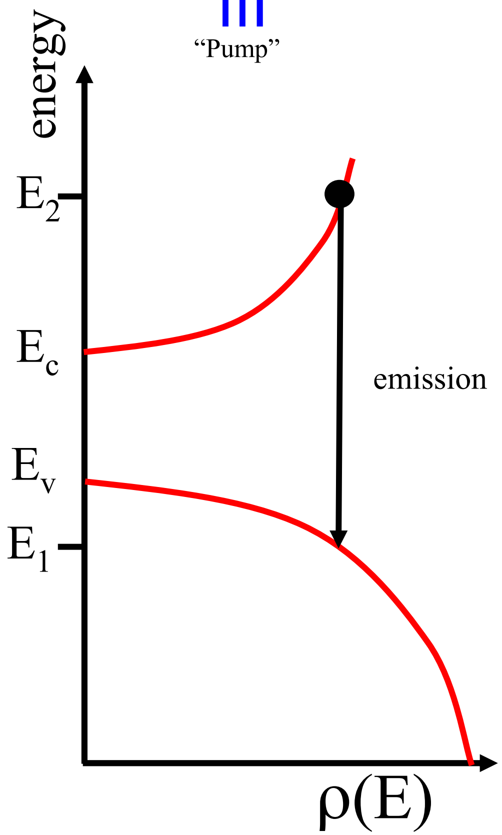
Discuss log scale on board (0).

Our goal in the next slides is to calculate quantitatively the blue curve.

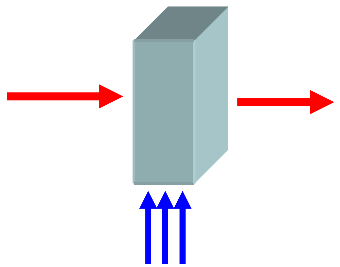
Optical emission:

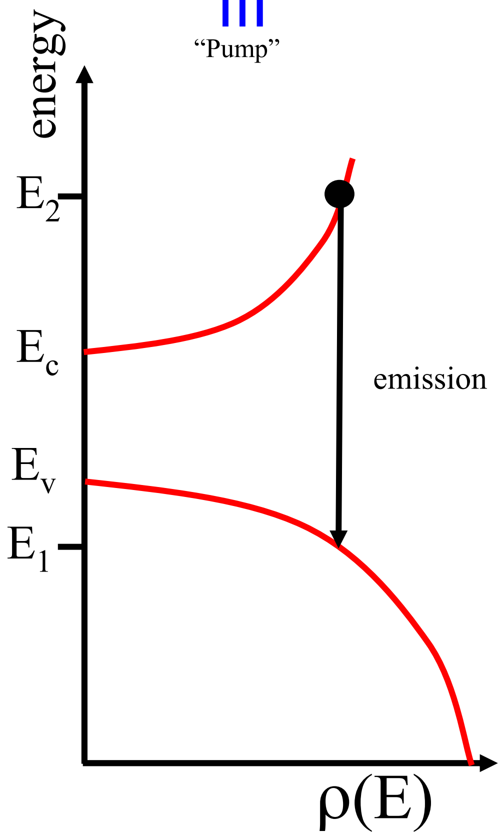


$$\hbar\omega_{photon} = E_2 - E_1$$



Optical emission:

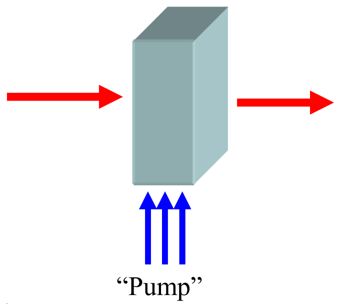


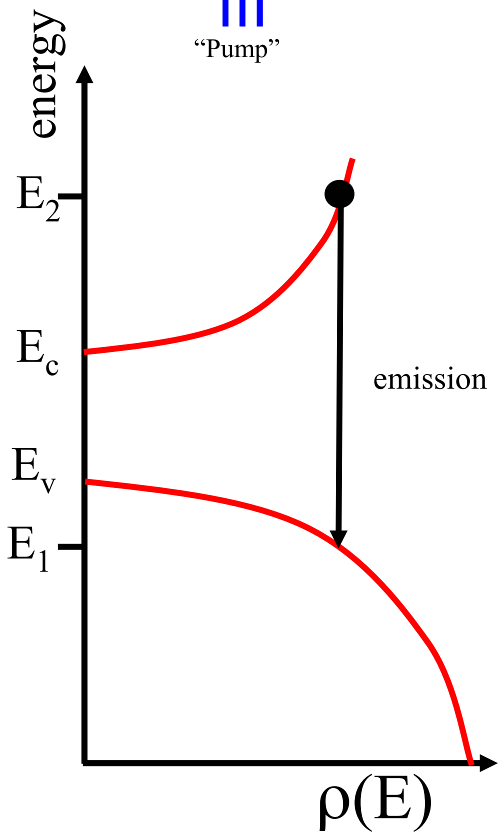


$$\hbar\omega_{photon} = E_2 - E_1$$

$$\hbar k_c = \sqrt{2m_e^*(E_2 - E_c)}$$

Optical emission:



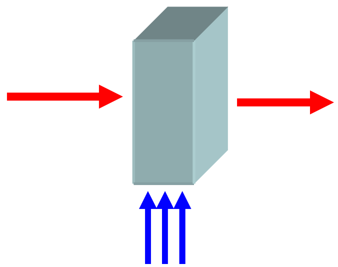


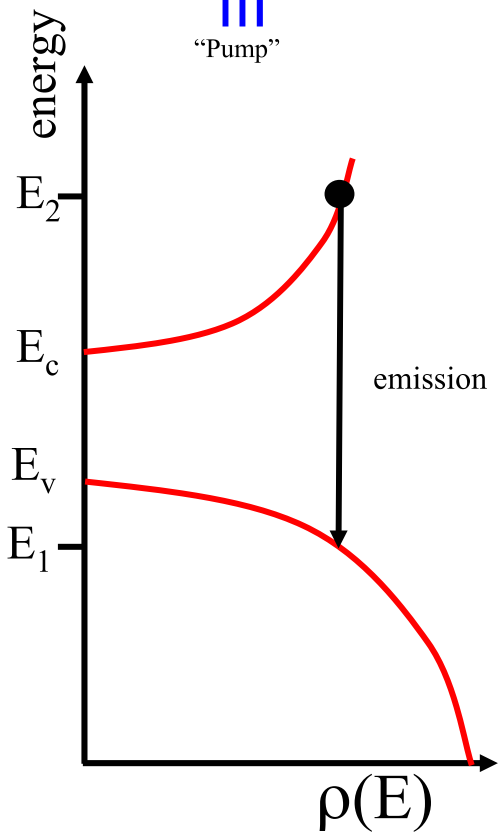
$$\hbar\omega_{photon} = E_2 - E_1$$

$$\hbar k_c = \sqrt{2m_e^*(E_2 - E_c)}$$

$$\hbar k_v = \sqrt{2m_h^*(E_v - E_1)}$$

Optical emission:





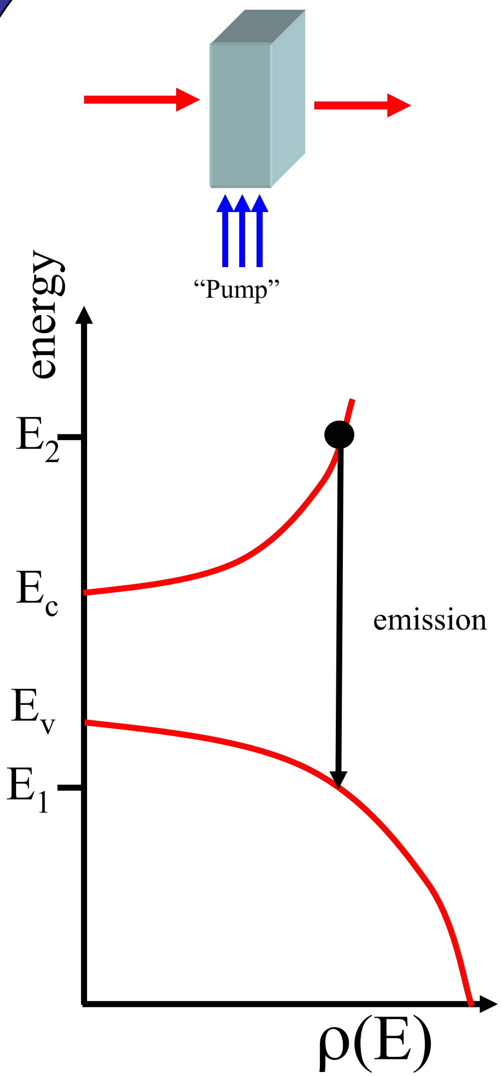
$$\hbar\omega_{photon} = E_2 - E_1$$

$$\hbar k_c = \sqrt{2m_e^*(E_2 - E_c)}$$

$$\hbar k_v = \sqrt{2m_h^*(E_v - E_1)}$$

$$\hbar k_v = \hbar k_c$$

Optical emission:



$$\hbar\omega_{photon} = E_2 - E_1$$

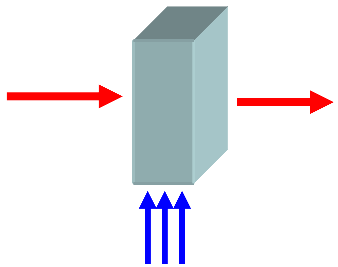
$$\hbar k_c = \sqrt{2m_e^*(E_2 - E_c)}$$

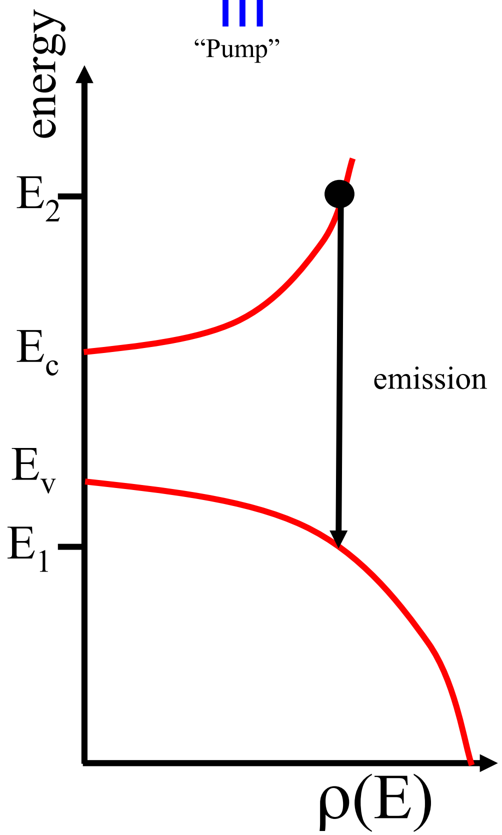
$$\hbar k_v = \sqrt{2m_h^*(E_v - E_1)}$$

$$\hbar k_v = \hbar k_c$$

$$\Rightarrow E_2 - E_c = \frac{m_h^*}{m_e^*}(E_v - E_1)$$

Optical emission:





$$\hbar\omega_{photon} = E_2 - E_1$$

$$\hbar k_c = \sqrt{2m_e^*(E_2 - E_c)}$$

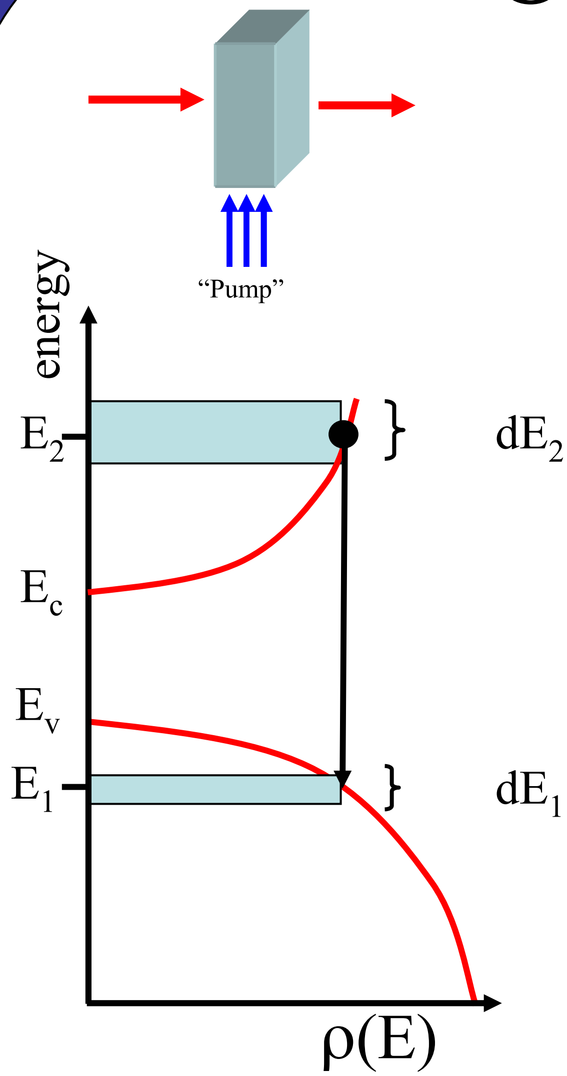
$$\hbar k_v = \sqrt{2m_h^*(E_v - E_1)}$$

$$\hbar k_v = \hbar k_c$$

$$\Rightarrow E_2 - E_c = \frac{m_h^*}{m_e^*}(E_v - E_1)$$

E_2 and E_1 are *not* centered around midgap.

Optical emission:

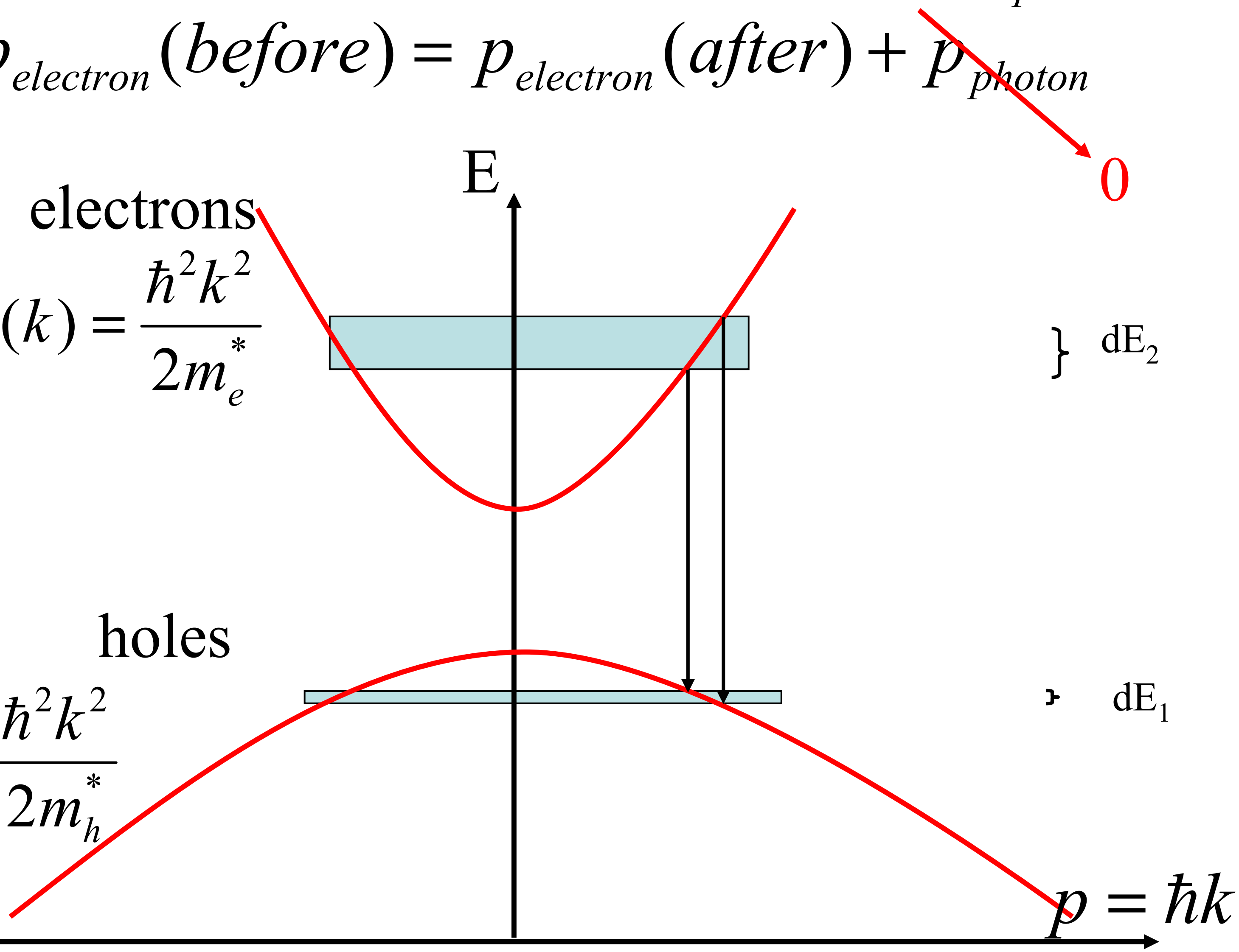


dE_1 and dE_2?

Optical emission:

$$E_{electron}(before) = E_{electron}(after) + \hbar\omega_{photon}$$

$$p_{electron}(before) = p_{electron}(after) + p_{photon}$$



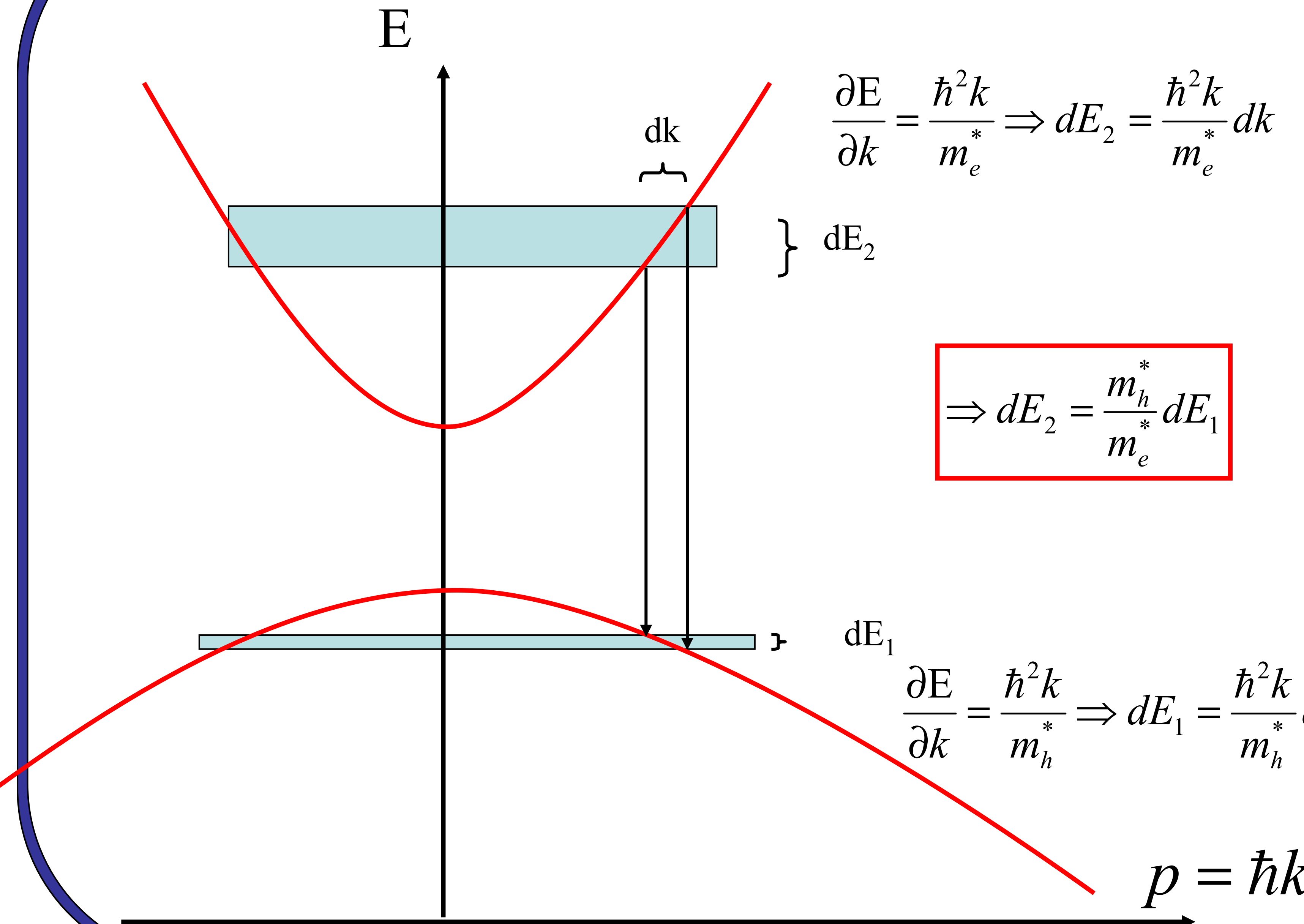
electrons

$$E(k) = \frac{\hbar^2 k^2}{2m_e^*}$$

holes

$$E(k) = \frac{\hbar^2 k^2}{2m_h^*}$$

Optical emission:

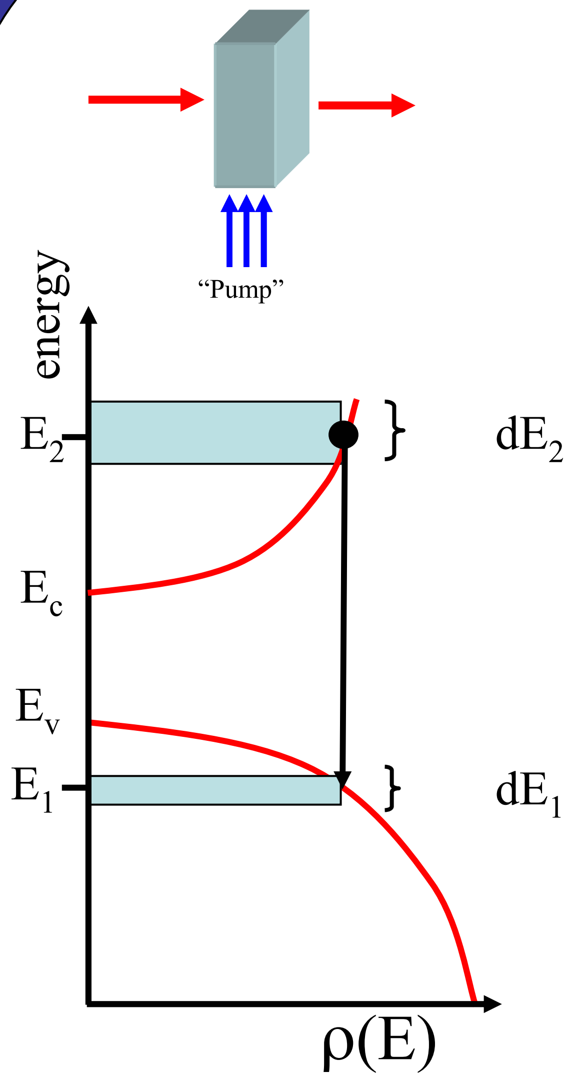


$$\frac{\partial E}{\partial k} = \frac{\hbar^2 k}{m_e^*} \Rightarrow dE_2 = \frac{\hbar^2 k}{m_e^*} dk$$

$$\Rightarrow dE_2 = \frac{m_h^*}{m_e^*} dE_1$$

$$\frac{\partial E}{\partial k} = \frac{\hbar^2 k}{m_h^*} \Rightarrow dE_1 = \frac{\hbar^2 k}{m_h^*} dk$$

So far:



$$E_2 - E_c = \frac{m_h^*}{m_e^*}(E_v - E_1)$$

$$dE_2 = \frac{m_h^*}{m_e^*} dE_1$$

So far, we have assumed:

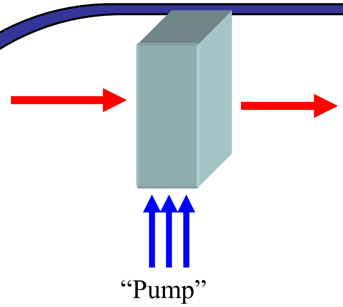
$$\hbar\omega_{photon} = E_2 - E_1$$

What if the incoming intensity is distributed in frequency such that I(ν)dν is the intensity between ν and ν+dν?

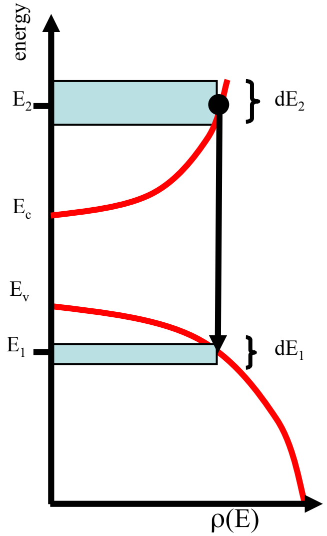
How many states are there such that an incident intensity with total intensity I(ν)dν participates?

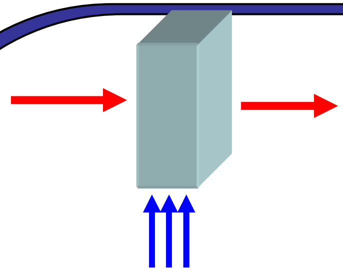
$$\rho_{jnt}(h\nu) = \frac{1}{2}\left[\frac{1}{\rho_c(E_2)} - \frac{1}{\rho_v(E_1)}\right]$$

So far:

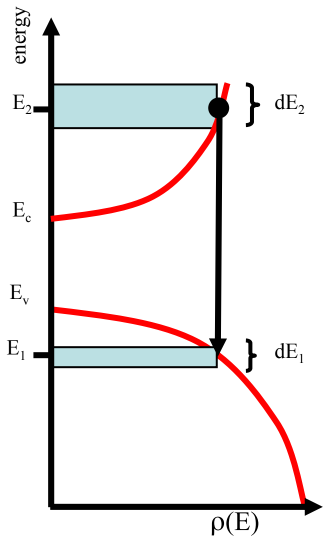


$$R_{1\to 2} = B_{1-2}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_v(E_1)\left(1-f_c(E_2)\right)\right]$$





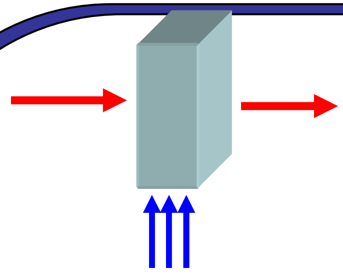
So far:

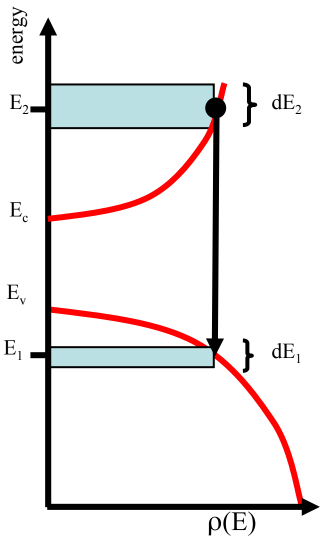


$$R_{1\to 2} = B_{1-2} \cdot \frac{1}{c} I(\upsilon) d\upsilon \cdot \rho_{jnt}(\nu) \cdot \left[f_v(E_1)(1 - f_c(E_2)) \right]$$

$$R_{2\to 1} = B_{2-1} \cdot \frac{1}{c} I(\upsilon) d\upsilon \cdot \rho_{jnt}(\nu) \cdot \left[f_c(E_2)(1 - f_v(E_1)) \right]$$

So far:

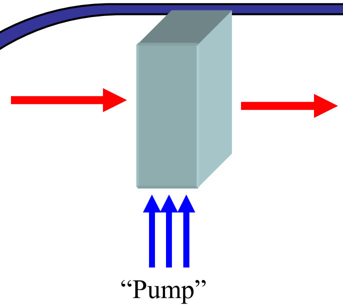




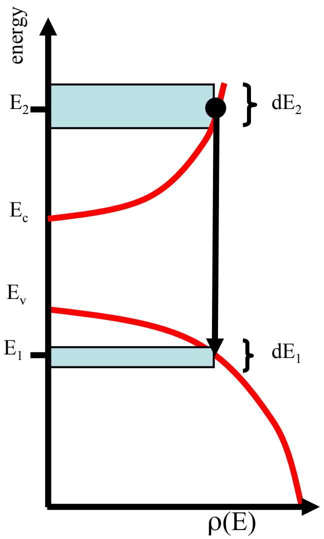
$$R_{1\to 2} = B_{1-2}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_v(E_1)\left(1-f_c(E_2)\right)\right]$$

$$R_{2\to 1} = B_{2-1}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_c(E_2)\left(1-f_v(E_1)\right)\right]$$

$$R_{2\to 1} - R_{1\to 2} = B_{2-1}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_c(E_2)-f_v(E_1)\right]$$



So far:

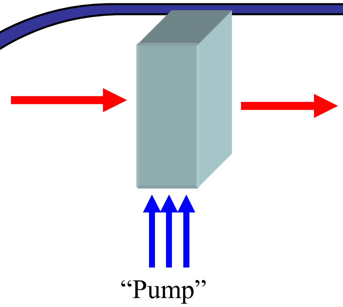


$$R_{1\to 2} = B_{1-2}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_v(E_1)\left(1-f_c(E_2)\right)\right]$$

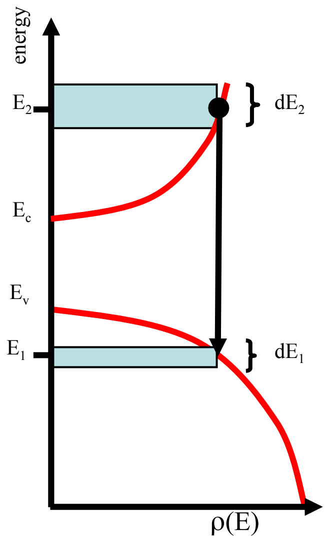
$$R_{2\to 1} = B_{2-1}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_c(E_2)\left(1-f_v(E_1)\right)\right]$$

$$R_{2\to 1} - R_{1\to 2} = B_{2-1}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_c(E_2)-f_v(E_1)\right]$$

Power emitted = hν * number of transitions/time = hν * (R_{21}-R_{12})



So far:



$$R_{1\to 2} = B_{1-2}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_v(E_1)\left(1-f_c(E_2)\right)\right]$$

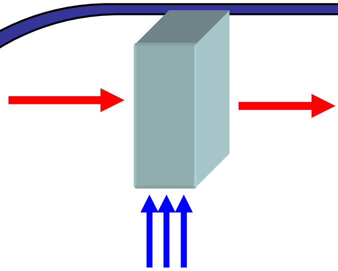
$$R_{2\to 1} = B_{2-1}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_c(E_2)\left(1-f_v(E_1)\right)\right]$$

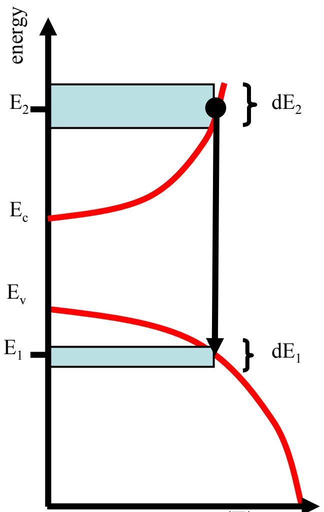
$$R_{2\to 1} - R_{1\to 2} = B_{2-1}\cdot\frac{1}{c}I(\upsilon)d\upsilon\cdot\rho_{jnt}(\nu)\cdot\left[f_c(E_2)-f_v(E_1)\right]$$

Power emitted = hν * number of transitions/time = hν * (R_{21}-R_{12})

$$\gamma(\upsilon) \equiv \frac{dI(\upsilon)/dz}{I(\upsilon)} = \frac{power/volume}{I(\upsilon)} = \frac{h\upsilon\cdot\left[R_{2\to 1}-R_{1\to 2}\right]}{I(\upsilon)d\upsilon}$$

So far:





$$R_{1\to 2} = B_{1-2} \cdot \frac{1}{c} I(\upsilon) d\upsilon \cdot \rho_{jnt}(\nu) \cdot \left[f_v(E_1)(1 - f_c(E_2)) \right]$$

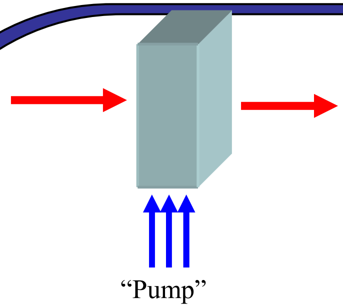
$$R_{2\to 1} = B_{2-1} \cdot \frac{1}{c} I(\upsilon) d\upsilon \cdot \rho_{jnt}(\nu) \cdot \left[f_c(E_2)(1 - f_v(E_1)) \right]$$

$$R_{2\to 1} - R_{1\to 2} = B_{2-1} \cdot \frac{1}{c} I(\upsilon) d\upsilon \cdot \rho_{jnt}(\nu) \cdot \left[f_c(E_2) - f_v(E_1) \right]$$

Power emitted = hν * number of transitions/time = hν * (R_{21}-R_{12})

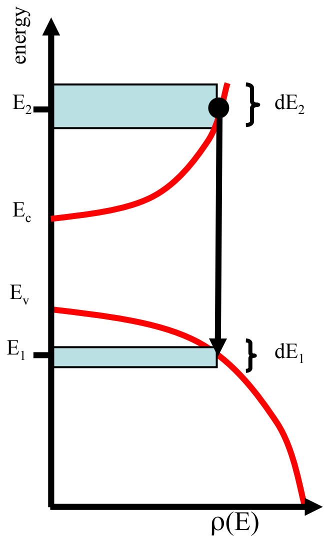
$$\gamma(\upsilon) \equiv \frac{dI(\upsilon)/dz}{I(\upsilon)} = \frac{power/volume}{I(\upsilon)} = \frac{h\upsilon \cdot \left[R_{2\to 1} - R_{1\to 2} \right]}{I(\upsilon) d\upsilon}$$

$$\gamma(\upsilon) = B_{2-1} \cdot \frac{1}{c} \cdot \rho_{jnt}(\nu) \cdot \left[f_c(E_2) - f_v(E_1) \right]$$



So far:

$$\gamma(\upsilon) = B_{2-1} \cdot \frac{1}{c} \cdot \rho_{jnt}(\nu) \cdot [f_c(E_2) - f_v(E_1)]$$

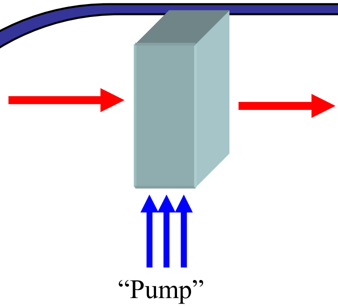


$$\rho_{jnt}(\nu) = \left(\frac{2m_e^* m_h^*}{m_e^* + m_h^*} \right)^{1/2} \sqrt{h\upsilon - E_{gap}}$$

$$\gamma(\upsilon) = K \cdot \sqrt{h\upsilon - E_{gap}} \cdot [f_c(E_2) - f_v(E_1)]$$

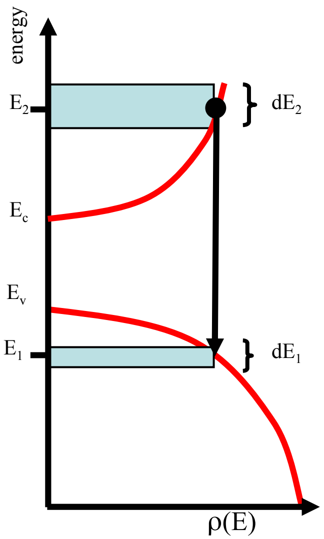
Three cases:

1) $h\nu < E_{gap}$
2) $E_{gap} < h\nu < F_n - F_p$
3) $h\nu > F_n - F_p$



Case one: $h\nu < E_{gap}$

$$\gamma(\upsilon) = K \cdot \sqrt{h\upsilon - E_{gap}} \cdot \left[f_c(E_2) - f_v(E_1) \right]$$

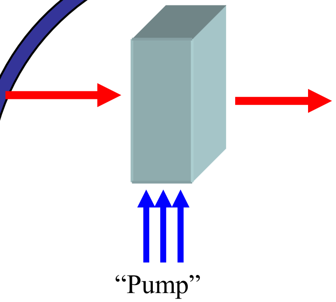


No absorption

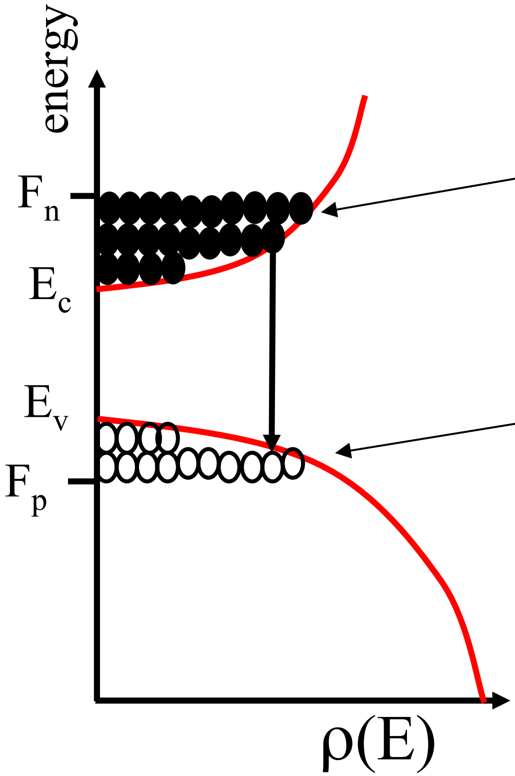
No emission

$\gamma=0$

Case two: $E_{gap} < h\nu < F_n - F_p$



$$\gamma(\upsilon) = K \cdot \sqrt{h\upsilon - E_{gap}} \cdot [f_c(E_2) - f_v(E_1)]$$



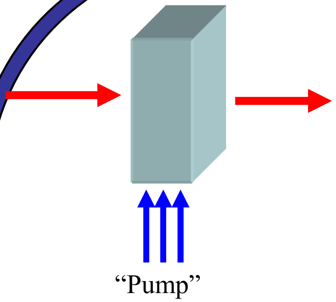
$$f_c(E_2) \approx 1$$

$$f_v(E_1) \approx 0$$

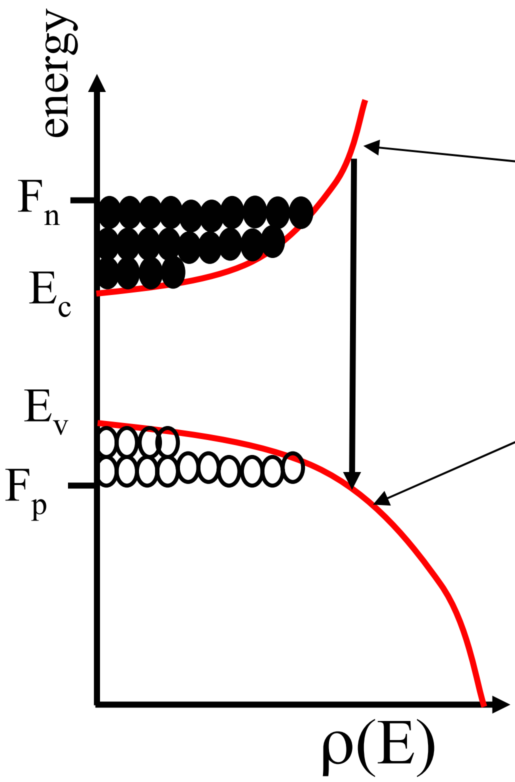
$$\gamma(\upsilon) \approx K \cdot \sqrt{h\upsilon - E_{gap}}$$

GAIN

Case three: > F_n-F_p



$$\gamma(\upsilon) = K \cdot \sqrt{h\upsilon - E_{gap}} \cdot \left[f_c(E_2) - f_v(E_1) \right]$$



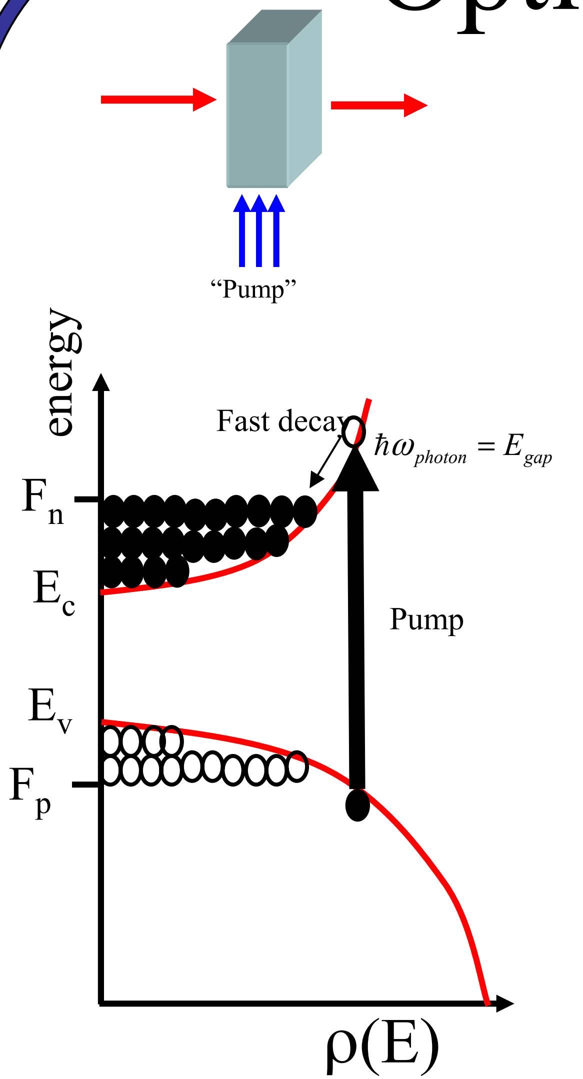
$$f_c(E_2) \approx 0$$

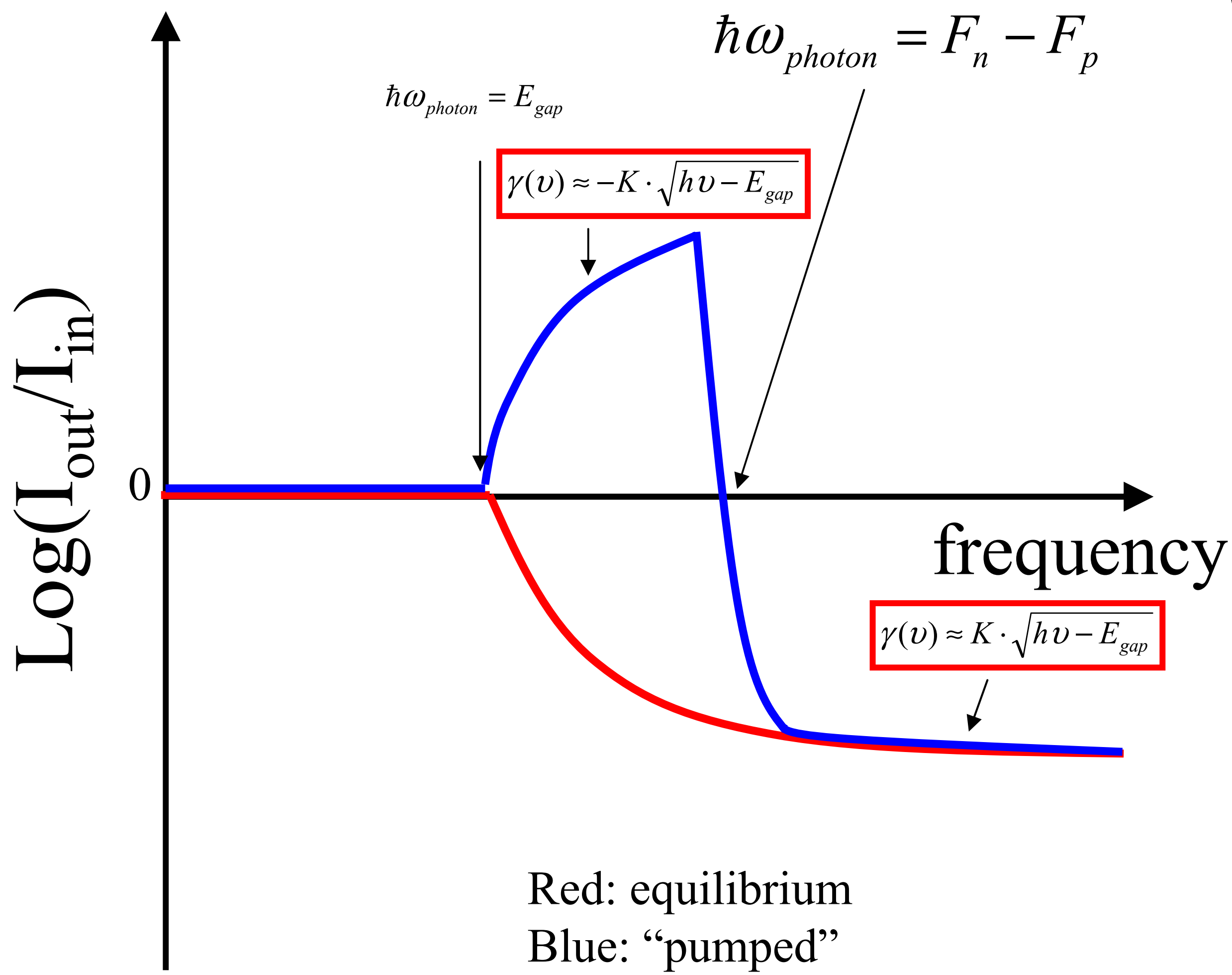
$$f_v(E_1) \approx 1$$

$$\gamma(\upsilon) \approx -K \cdot \sqrt{h\upsilon - E_{gap}}$$

LOSS

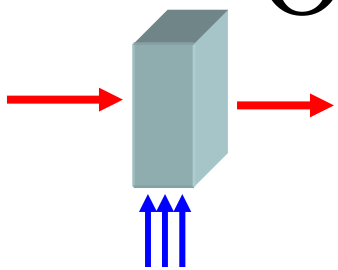
Optical absorption (?):

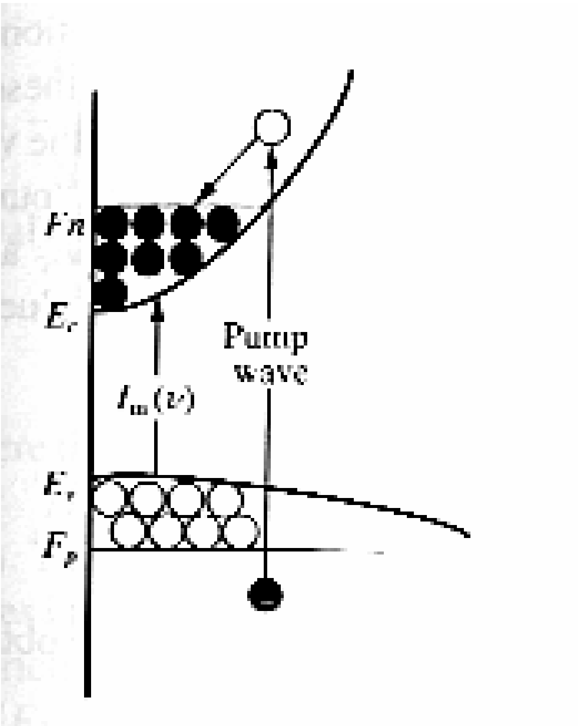




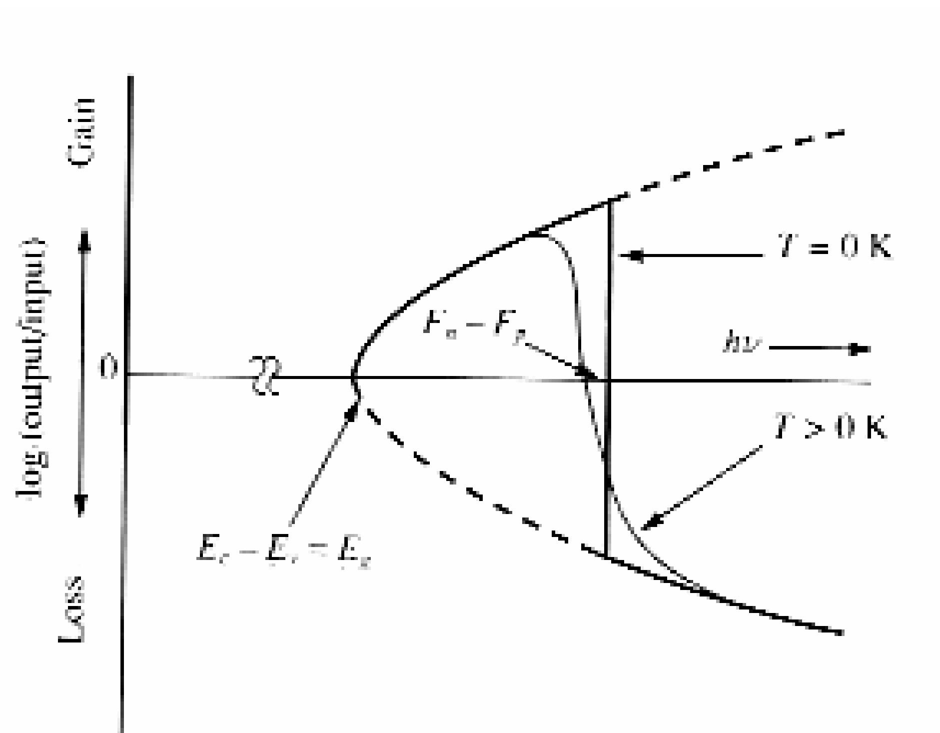
Our goal in the next slides is to calculate quantitatively the blue curve.

Optical absorption (?):





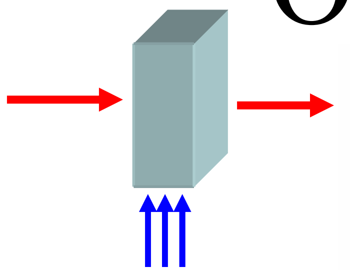
(b) The band diagram



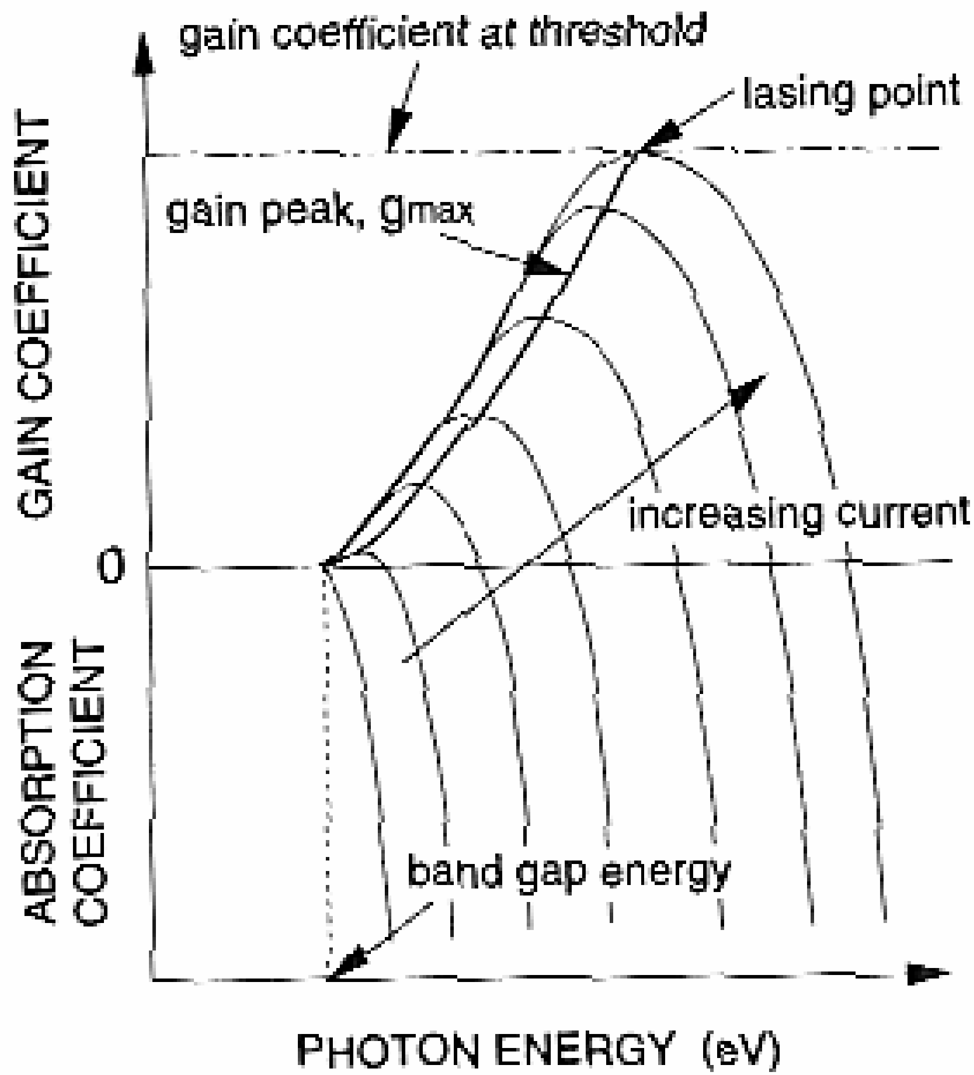
(c) The "data"

From Verdeyen

Optical absorption (?):

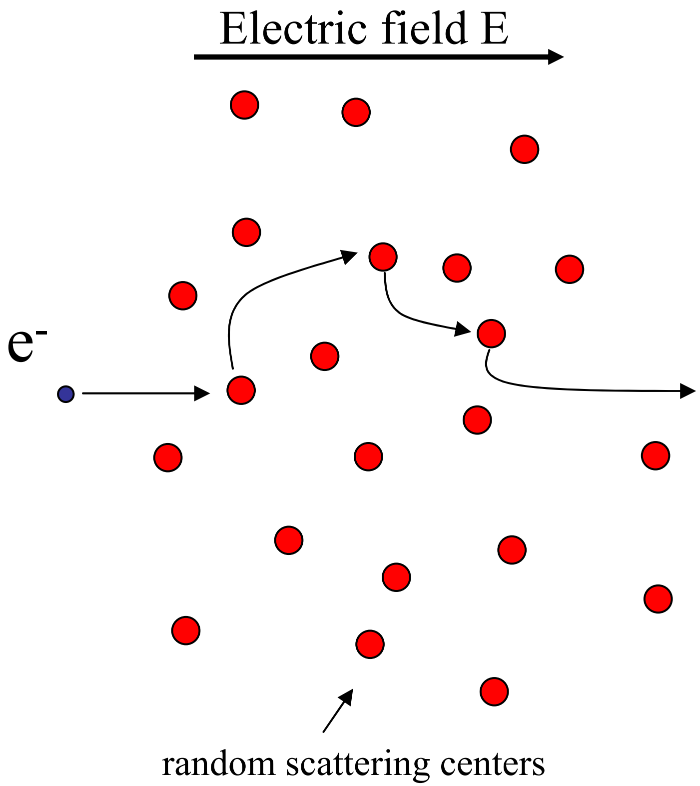


Discuss log scale on board (0).

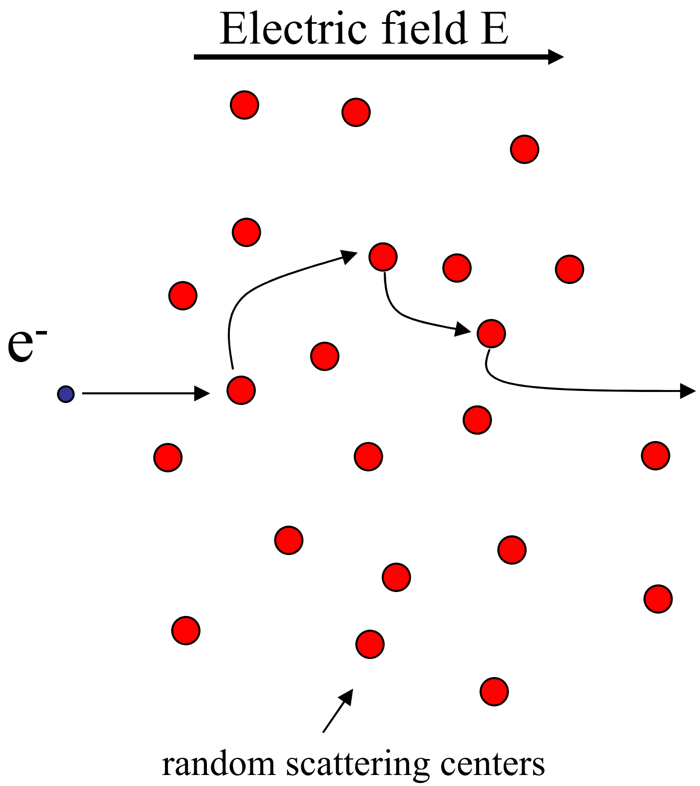


From Fukuda, Optical Semiconductor Devices

Drude model: Drift current

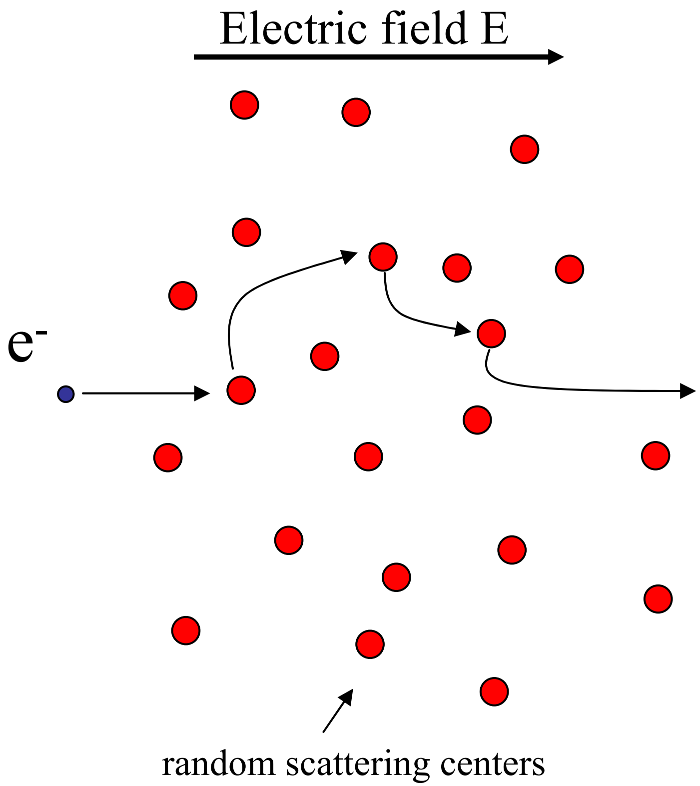


Drude model: Drift current



$$F = ma$$

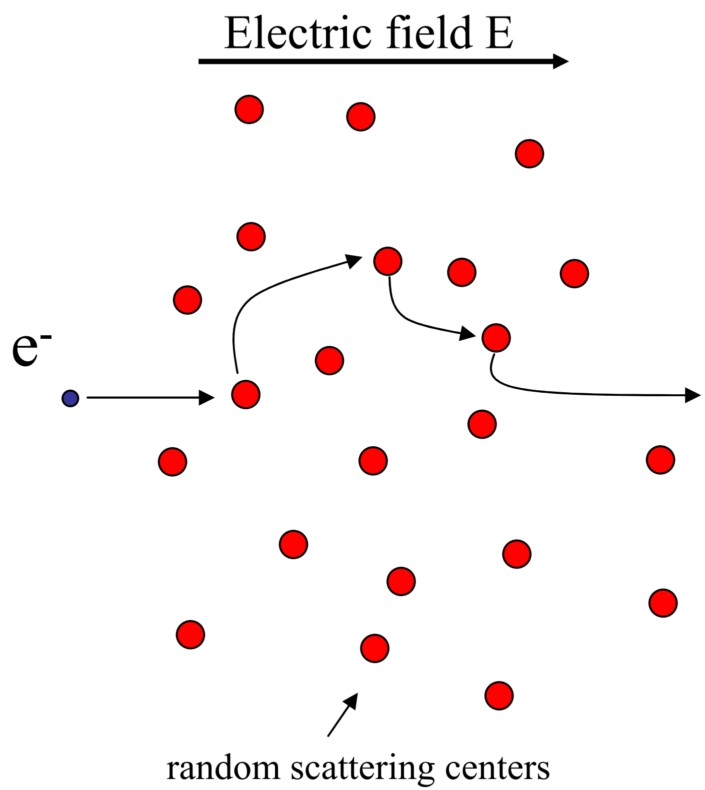
Drude model: Drift current



$$F = ma$$

$$eE = m\frac{\partial v}{\partial t}$$

Drude model: Drift current

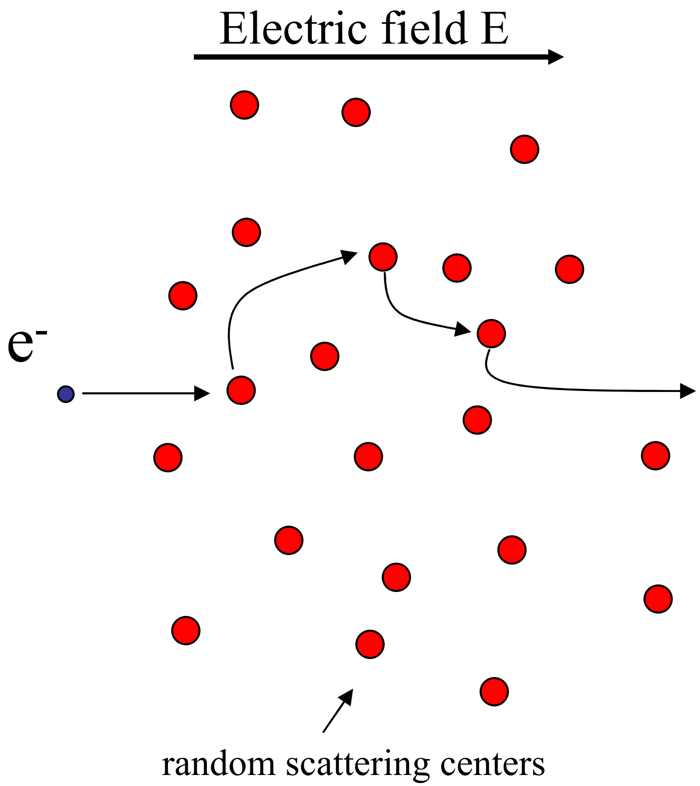


$$F = ma$$

$$eE = m\frac{\partial v}{\partial t}$$

$$v_{drift} = \frac{e\tau}{m}E$$

Drude model: Drift current



$$F = ma$$

$$eE = m\frac{\partial v}{\partial t}$$

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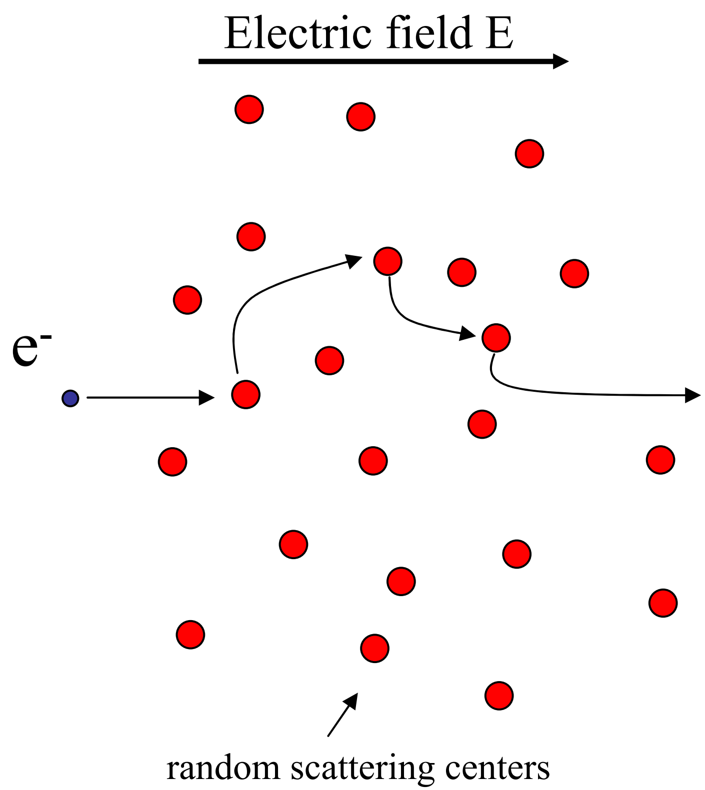
Drude model: Drift current



$$F = ma$$

$$eE = m\frac{\partial v}{\partial t}$$

$$v_{drift} = \underbrace{\frac{e\tau}{m}}_{\mu} E$$

$$J = nev = \frac{ne^2\tau}{m}E = e \cdot \mu \cdot n \cdot E$$

Diffusion current

$$J = eD\frac{dn(x)}{dx}$$

Total current

$$J_n = e \cdot \mu_n \cdot n \cdot E + eD_n \frac{dn(x)}{dx}$$

E, n can depend on x!

Holes:

$$J_p = e \cdot \mu_p \cdot p \cdot E - eD_p \frac{dp(x)}{dx}$$

Diffusion equation

Cross section area of length dx: (draw on board)

$$\frac{\partial n}{\partial t} = \frac{1}{e}\frac{J(x) - J(x+\Delta x)}{\Delta x} - \left(\frac{1}{\tau_n}\right)n$$

Diffusion equation

Cross section area of length dx: (draw on board)

$$\frac{\partial n}{\partial t} = \frac{1}{e}\frac{J(x) - J(x+\Delta x)}{\Delta x} - \left(\frac{1}{\tau_n}\right)n$$

$$\Rightarrow \frac{\partial n}{\partial t} = \frac{1}{e}\frac{\partial J(x)}{\partial x} - \left(\frac{1}{\tau_n}\right)n$$

Diffusion equation

Cross section area of length dx: (draw on board)

$$\frac{\partial n}{\partial t} = \frac{1}{e}\frac{J(x) - J(x+\Delta x)}{\Delta x} - \left(\frac{1}{\tau_n}\right)n$$

$$\Rightarrow \frac{\partial n}{\partial t} = \frac{1}{e}\frac{\partial J(x)}{\partial x} - \left(\frac{1}{\tau_n}\right)n$$

$$J = eD\frac{dn(x)}{dx}$$

Diffusion equation

Cross section area of length dx: (draw on board)

$$\frac{\partial n}{\partial t} = \frac{1}{e} \frac{J(x) - J(x + \Delta x)}{\Delta x} - \left(\frac{1}{\tau_n} \right) n$$

$$\Rightarrow \frac{\partial n}{\partial t} = \frac{1}{e} \frac{\partial J(x)}{\partial x} - \left(\frac{1}{\tau_n} \right) n$$

$$J = eD \frac{dn(x)}{dx}$$

$$\frac{\partial n}{\partial t} = D \frac{\partial^2 n}{\partial x^2} - \left(\frac{1}{\tau_n} \right) n$$

Steady state

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - \left(\frac{1}{\tau_n}\right)n = 0$$

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Steady state

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - \left(\frac{1}{\tau_n}\right)n = 0$$

$$\Rightarrow D\frac{\partial^2 n}{\partial x^2} = \left(\frac{1}{\tau_n}\right)n$$

$$\Rightarrow n(x) = n(x=0)\cdot\exp\left(-\frac{x}{\sqrt{D\tau_n}}\right)$$

Steady state

$$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - \left(\frac{1}{\tau_n}\right)n = 0$$

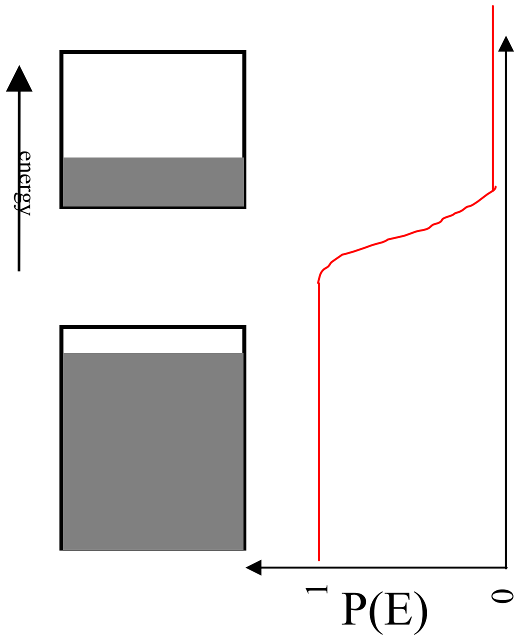
$$\Rightarrow D\frac{\partial^2 n}{\partial x^2} = \left(\frac{1}{\tau_n}\right)n$$

$$\Rightarrow n(x) = n(x=0)\cdot \exp\left(-\frac{x}{\sqrt{D\tau_n}}\right)$$

$$\sqrt{D\tau_n} \equiv \text{diffusion length}$$

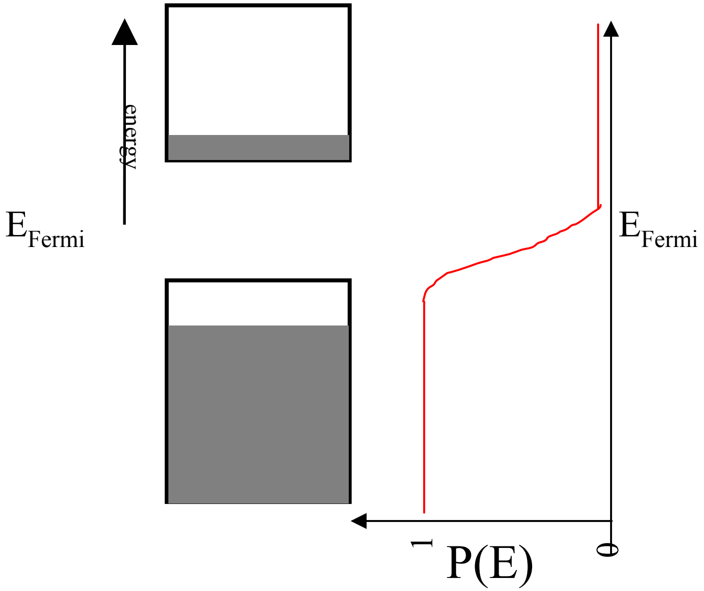
Last time:

n type:



$n > p$

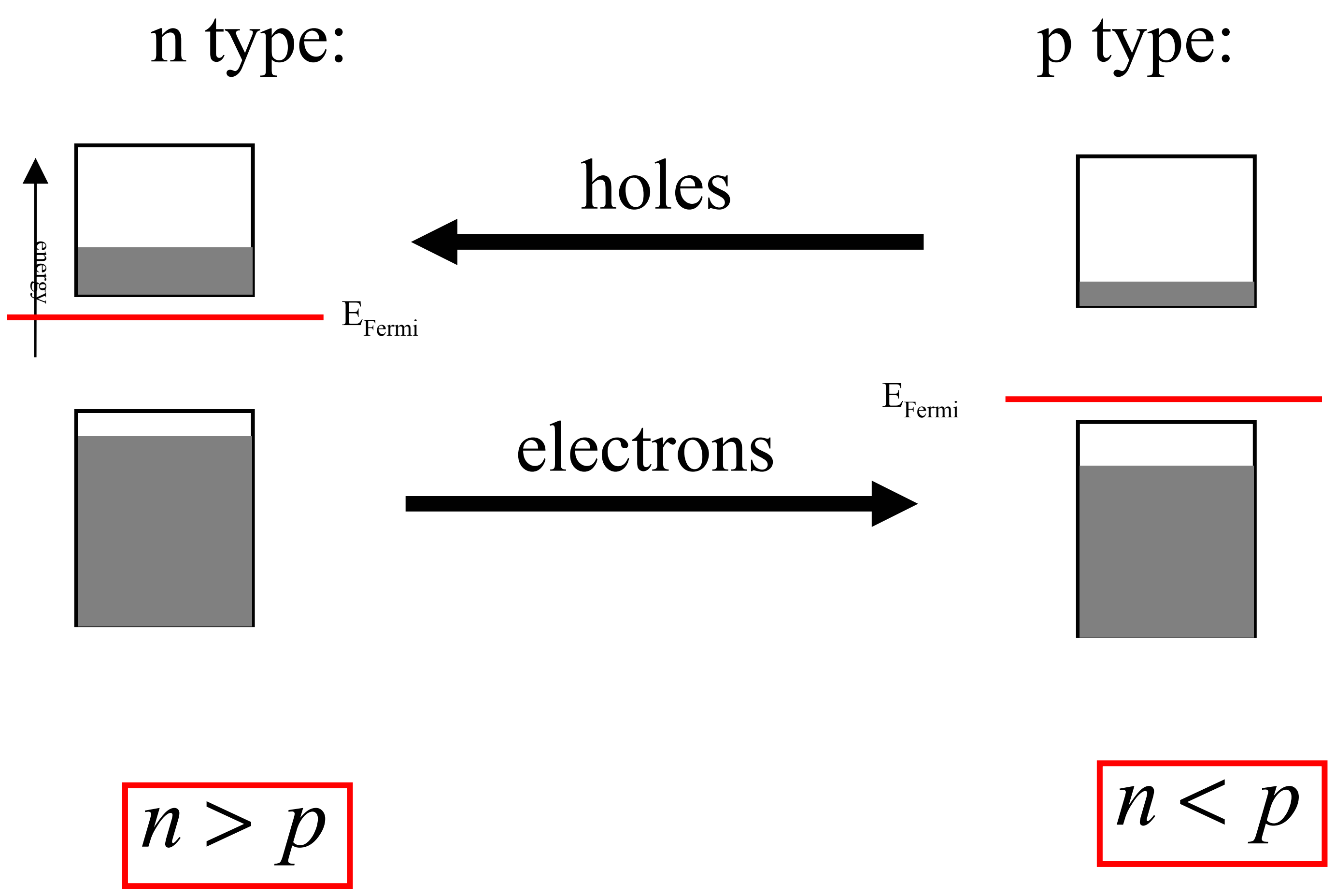
p type:



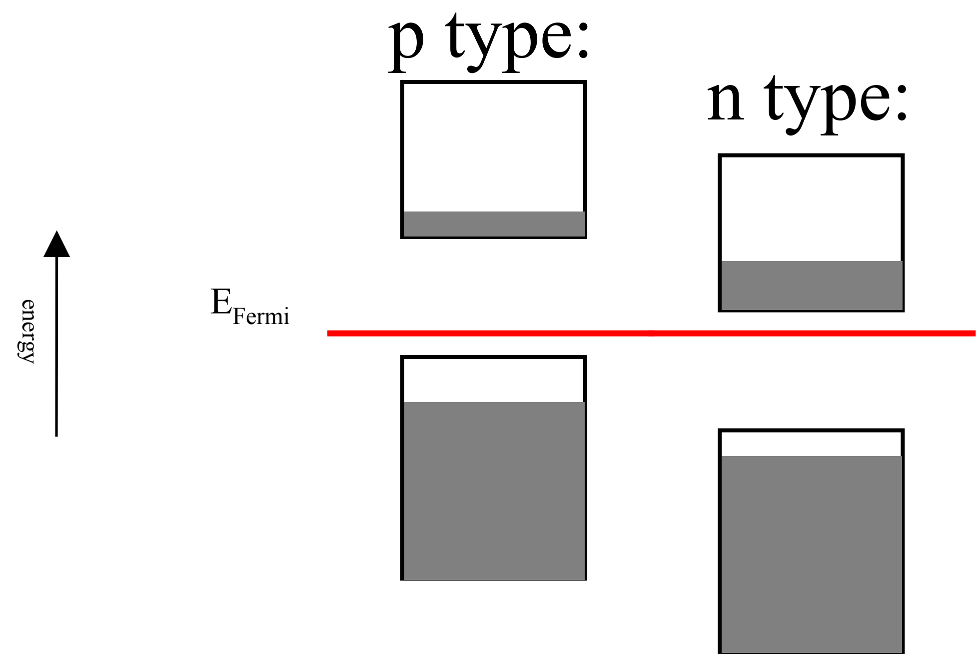
$n < p$

What if we bring n and p type together?
p n diode

p n diode



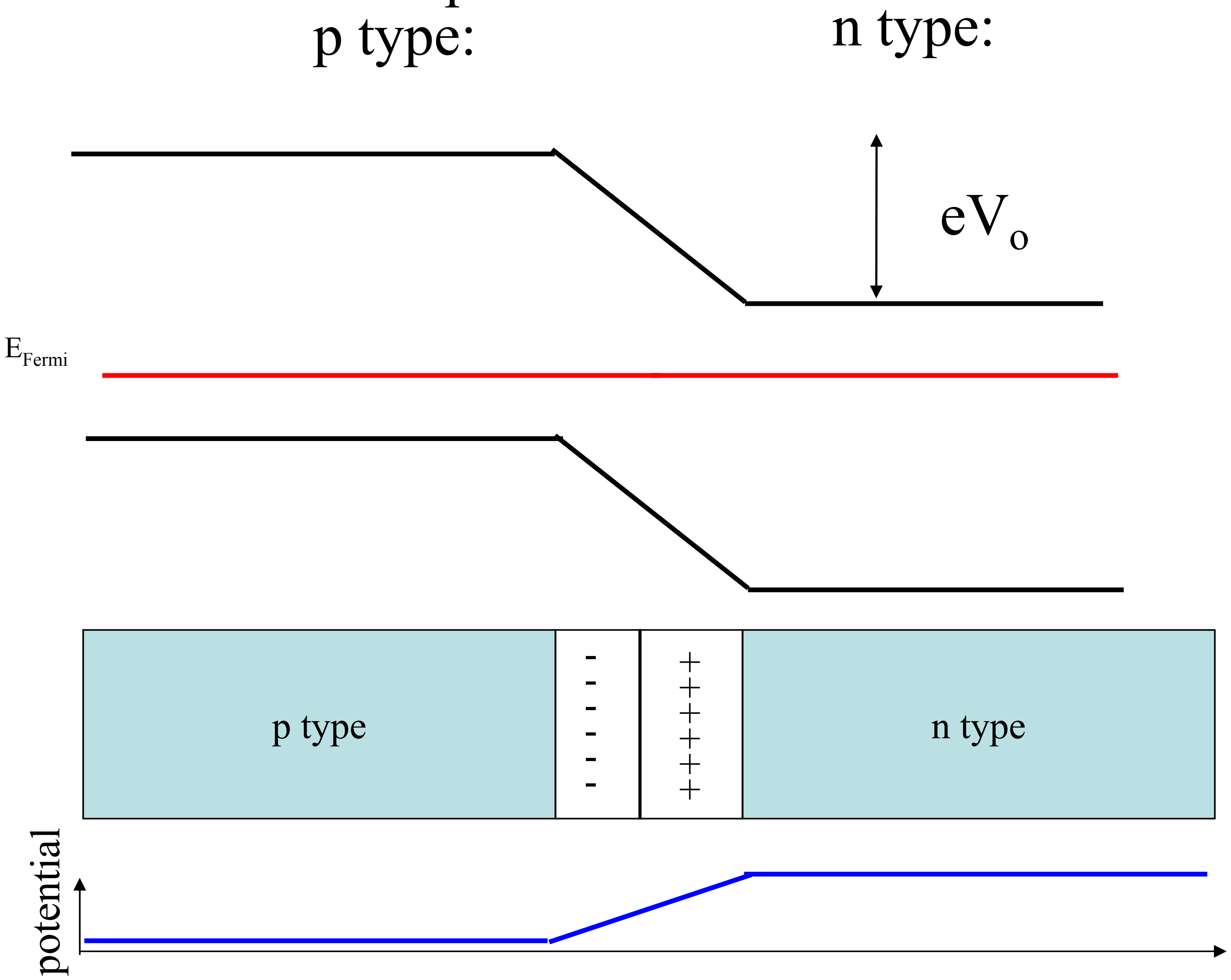
p n diode



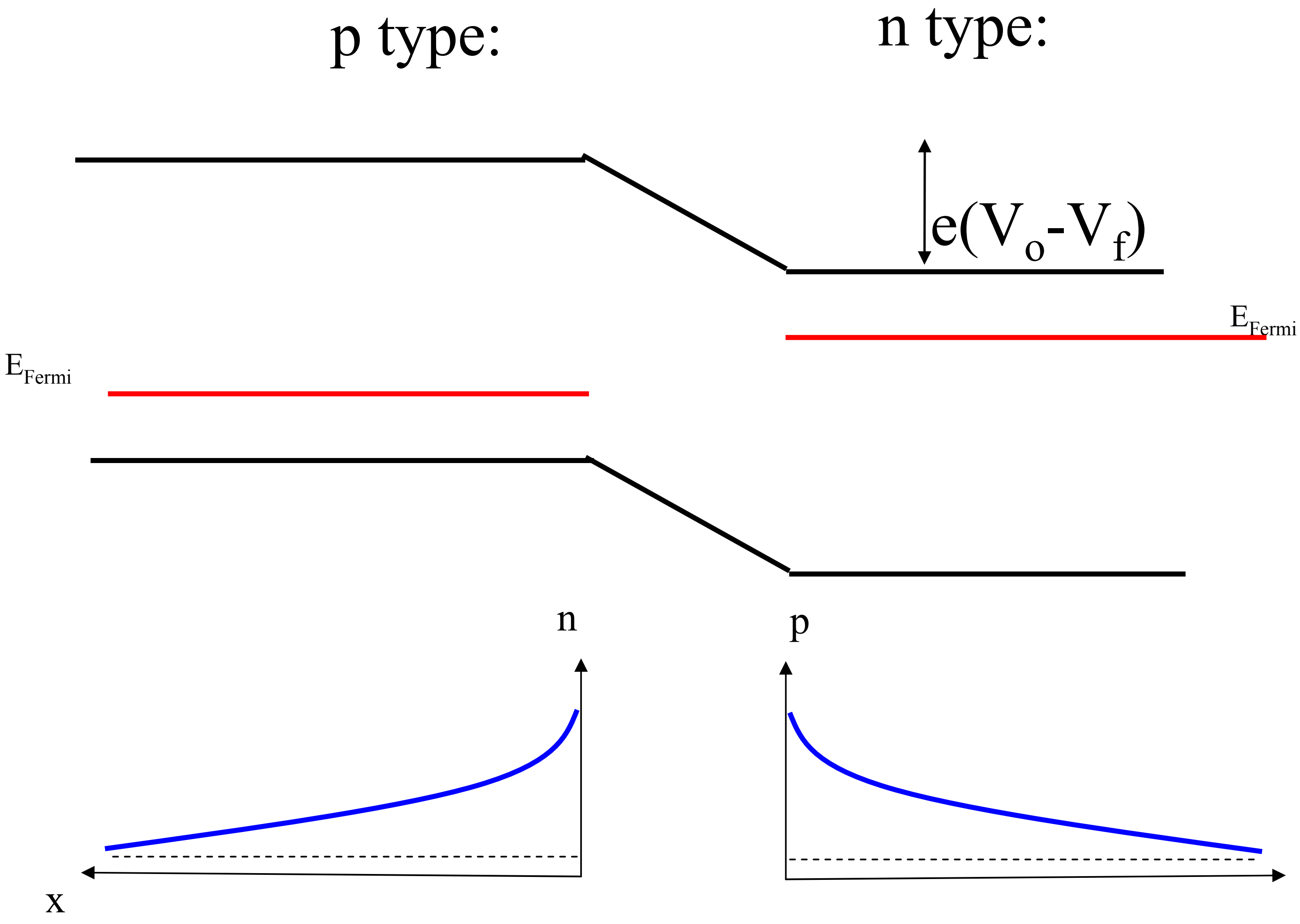
$n < p$

$n > p$

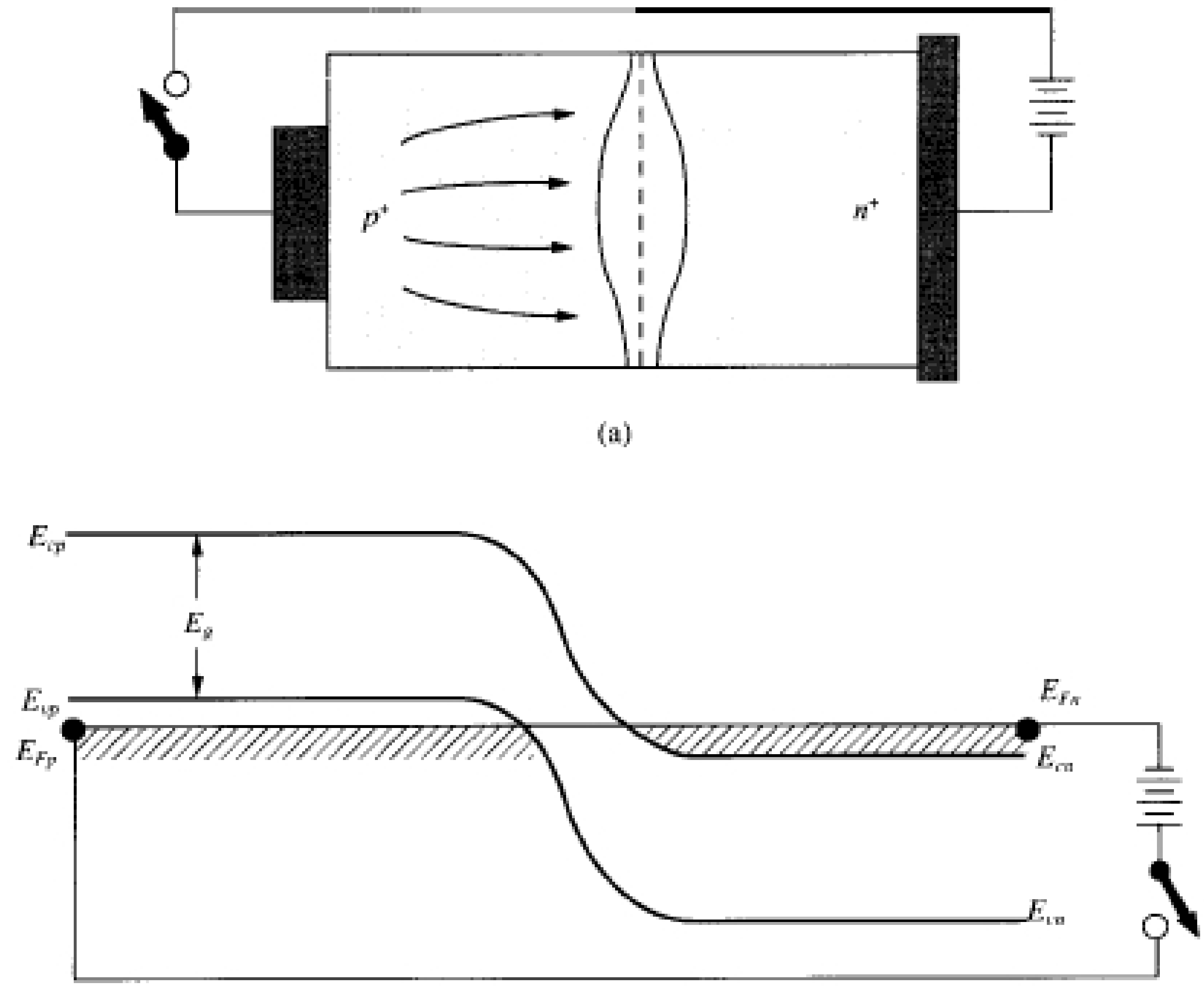
p n diode



Forward bias



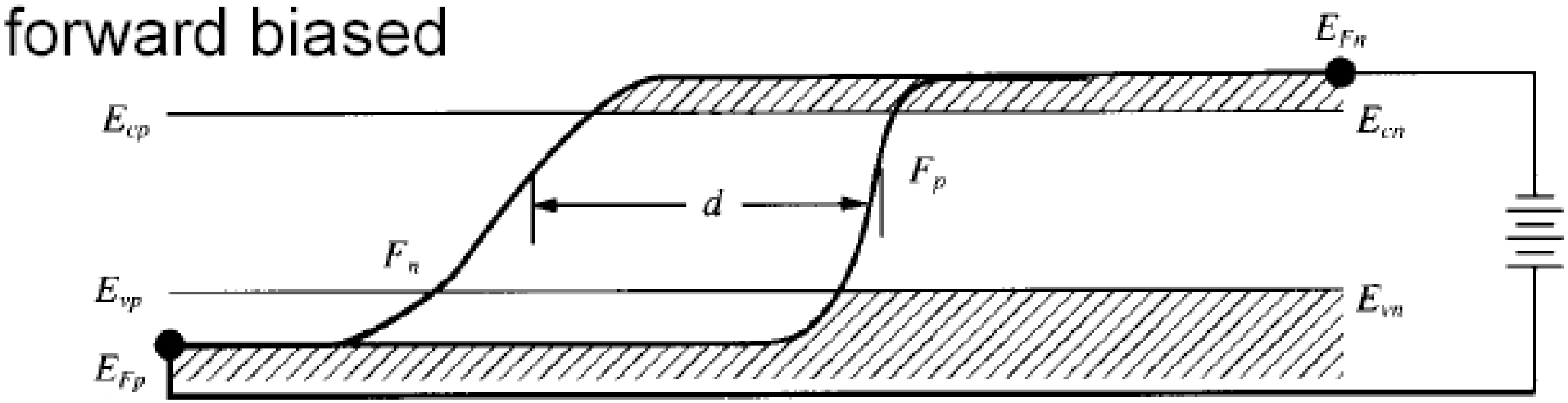
Laser diode



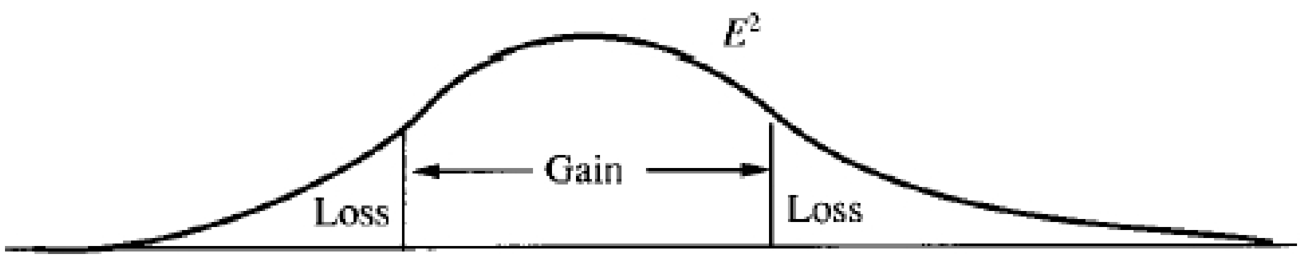
(a)

(b)

Laser diode



(c)



(d)

Threshold current

- Injected electrons = current
- Recombination rate ~ n p
- Need input current = recombination rate (steady state)
- Need n,p ~ 10^{18} cm^{-3}
- J ~ 10 kA/cm^2 VERY BIG!

p n diode